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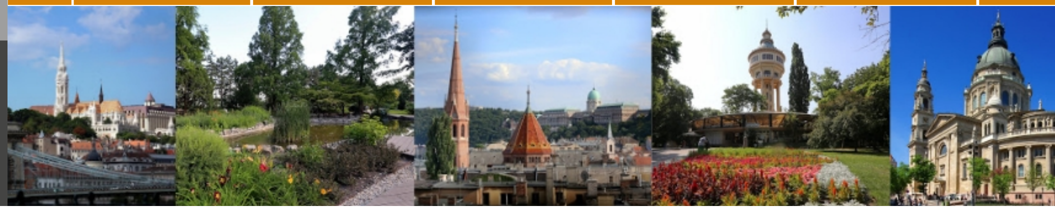
29 June - 2 July 2019 | Budapest, Hungary



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A roadmap to achieving readiness for macro adoption of distributed ledger technology (DLT) in the construction industry

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Abstract

Applications and uses cases of distributed ledger technology (DLT) are increasingly attracting interest in the construction industry. However, DLT in construction is still considered a nascent field of research and practical applications of DLT in construction are at the very early readiness stages. This paper builds on a previously developed socio-technical systems framework for DLT in construction (i.e. Li et al., 2019) built on four dimensions of technical, process, policy and social, and proposes a roadmap to achieving readiness for macro adoption of DLT in the construction industry. First, the paper reviews existing readiness and adoption models and technology roadmaps for new technological innovations in the context of DLT highlighting their strengths and detailing why they are not suitable for DLT. Then, drawing on experience of existing models as a basis, it proposes a four-stage roadmap to readiness for adoption of DLT in the construction industry. The four-stage DLT Roadmap incorporates Conceptualisation, Appraisal, Preparation and Implementation. This roadmap is intended to provide the industry with a comprehensive framework to support adoption and diffusion of DLT for specific use cases. Future work will involve proposal of guidelines for each of the four dimensions across the four-stage DLT Roadmap and testing through workshop-identified use cases of DLT in construction.

Keywords: distributed ledger technology (DLT); blockchain; technology roadmap; macro adoption; readiness; construction industry.

1. Introduction

Distributed ledger technology (DLT) will produce the most benefits when adoption reaches a critical mass and the community consists of many relevant members [1]; in the construction industry this necessitates extensive market-wide adoption of the system. This could involve mobile applications linked to DLT that record activities or performance as transactions on a distributed ledger as part of a construction project or facilities management of a building, or supply chain integration with Building Information Modelling (BIM) models where procurement decisions and shipping and delivery of goods and services are automatically uploaded to the ledger as the information model is simultaneously updated. These use cases bring about a number of challenges such as: (a) the consistency between the digital environment (e.g. information models, documentations, data), agreements (e.g. as in the information container), and the actual built assets (e.g. physical assets, goods, and services); (b) the need for recording key decisions about both the digital and the physical environment of a built asset across its lifecycle from conception through design, planning, construction, to operation and demolition [2,3]; and (c) the successful integration of required technologies – BIM, DLT, Internet of Things (IoT) and smart contracts as discussed in [3]. The characteristics of DLT (e.g. redefining trust, decentralisation, anonymity) have the potential to support solutions to these challenges.

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This paper contributes to the body of research through proposal of a roadmap for achieving readiness for adoption of DLT in the construction industry. This a continuation of the extended socio-technical framework developed in [4] that assimilates four dimensions of technical, policy, process and social, and proposes two models – DLT Four-Dimensional Model and DLT Actors Model. A roadmap for new technologies is both a strategic and operational approach to support organisations and industries in charting technology issues relevant to their future success [5]. This is done by assessing current readiness models and roadmaps for new technology in construction and other industries, which were used as a basis for development of the DLT Roadmap for construction. The approach proposed in this paper may be applicable to other technological innovations and industries; however, terms and concepts may need to be redefined to be appropriate for the use/use case for which they are intended.

Several terms used throughout this paper do not have universally accepted definitions in the existing literature. Terms often have different meanings at different stages of a technology's adoption whether at the implementation stage or at the diffusion stage that follows [6]. For the purpose of this study, each of the terms' definitions are clarified: *macro* defines the scope of adoption which is at the industry scale within one defined market (e.g. a country) and includes the different user groups (individuals, organisational departments/teams, entire organisations, inter-organisational projects) such as those identified in the DLT Actors Model [4]. This study does not differentiate between these groups, it considers them as a whole making up the industry at the macro scale. *Adoption* is referred to as a '*state'* or a '*milestone'* that is achieved within a market once the corresponding construction sector perceives the use of DLT in construction as the norm. There will be varying levels of diffusion (i.e. rates of adoption) for the different use cases of DLT in construction by the time this milestone is reached. This milestone is preceded by '*implementation'* which refers to the wilful act of inserting DLT into the construction industry for selected applications once readiness has been achieved for the corresponding use cases. *Readiness* is defined by the point at which the industry is in a suitable position to implement DLT across organisations and projects; it refers to the preparation and propension required to adopt DLT and involves being in a state where policies, processes and systems are sufficiently robust to withstand adoption of the new system.

The next section looks at technology adoption in construction and highlights existing models and roadmaps that supported this study; section 3 proposes the roadmap to achieving readiness for adoption of DLT in construction; and section 4 provides discussion and concludes the paper.

2. Adoption of digital innovations

Understanding how new technological innovations are adopted in construction generally will help in understanding the conditions required for DLT. This section considers the adoption of BIM to date along with the challenges it faced. Then, it highlights adoption/maturity models used to assess DLT and reviews existing models and roadmaps to support development of the DLT Roadmap proposed in this paper.

As BIM is the current expression of technological innovation in construction it is most appropriate to draw comparisons for DLT. BIM is a set of technologies, processes and policies affecting the industry's deliverables, relationships and roles [6]. While BIM offers many benefits and improvements to collaboration across the industry, there have been and still are many barriers to its widespread adoption. Barriers are offered including "lack of initiative and training, fragmented nature of the AEC industry, varied market readiness across geographies, and industry's reluctance to change existing work practice" ([7], p. 989). Key barriers include lack of senior management support, cost of implementation, scale of culture change required, other competing initiatives, lack of supply chain buy-in, staff resistance and ICT literacy, and legal uncertainties [8]. [9] add "the lack of tangible benefits for all parties involved or the understanding of the business value of BIM; the lack of experience within the workforce; the lack of universal use; the resistance to change; the contract type/project delivery method inhibiting technology adoption, and time and cost" (p. 9). While these are BIM-specific, each was identified as a possible barrier to adoption of DLT in construction and were central to developing a framework for implementation of DLT as seen in [4].

There is no academic literature on the adoption of DLT in the construction industry at the macro scale. Studies have been conducted across other industries and at different scales of analysis such as: logistics and supply chain management at an individual scale [10]; maturity of blockchain generally [11]; acceptance of Bitcoin and Blockchain at an individual scale [12]; and organisational adoption of blockchain [13].

2.1. Existing models for assessing readiness of innovations

Models to assess readiness or maturity have been used for many years and many variations exist. They assess the gap between current and desired state in respect of an innovation or activity, however, they often omit roadmaps to achieving the desired state [14]. Roadmaps for adoption of new technology are more appropriate for DLT than maturity models at this stage in its development. Models and roadmaps key to this research are forthwith discussed.

Rogers' [15] *Innovation-Decision Process* supports evaluation and decisions of a new idea regarding adoption. The five stages are knowledge, persuasion, decision, implementation and confirmation. The process is offered as applicable at different scales including individual or other decision-making unit [15].

Technical Readiness Levels (TRL), the most widely used method of assessing an individual technology's maturity [16–18], is effective in assessing the current level of a technology. However, it does not look at the surrounding nor operational environments of the technology; it does not offer guidance of the uncertainty to be expected during maturity of a system; nor does it offer a comparative analysis technique to assimilate against other TRLs [16]. The majority of complex systems fail at integration points with other technologies, therefore, [16] propose a readiness model to address these challenges, *Systems Readiness Levels (SLR)*. SLR incorporates TRL and *Integration Readiness Levels (IRL)* – measurement of the interactions of various technologies and comparison of the maturity between integration points [16]. The model is applicable to different applications and architectures [19] thus supports the socio-technical framework developed for implementation of DLT in construction. However, it focuses solely on technological systems and their interaction with other technologies; it is missing the interrelation between technologies and the remaining dimensions of process, policy and social as in the DLT Four-Dimensional Model. Similar readiness levels scales aligning to policy, process and social include a taxonomy of *Policy Readiness Levels (PRL)* [20] that mimics TRL [21] "for research directed towards the design of institutional and/or regulatory policies" ([20], p. 393); *Process Readiness Levels (PRL)* appearing alongside Material Readiness Levels (MRL) in the context of aerospace/space exploration [22,23]; and *Societal Readiness Levels (SRL)* to assess the level of societal adaptation of a social project, technology, product, process, intervention or social or technical innovation to be integrated into society [24].

Technology roadmaps follow six steps: 1) identify the needs and drivers; 2) identify products or services to meet the needs and the drivers; 3) identify technologies to support the products or services; 4) establish the linkages among the first three steps above; 5) develop plans to acquire or develop the technologies; 6) assign resources to accomplish the plans for acquisition and development [5]. A 12-step roadmap for organisational adoption of Information Technology and Infrastructure Library (ITIL) is proposed by [25] focusing on adoption within an organisation. [26] builds on the technology roadmap developed by [27] which is adaptable to both organisation and industry scales. Its three phases are: preliminary activity, development of the technology roadmap and follow-up activity. [27]'s process was developed with a focus on product/process driven needs; [26] extends the process for disruptive technologies. As DLT involves more than just adoption of a new technology [4], this process alone is not suitable to support its implementation. [28] use this process to develop a roadmap for smart city development in Korea. [29] proposes an Innovation Roadmap utilising a multi-layer, timeline-based structure incorporating technological change, industrial change, policy change and social change and the dynamics of regime and niche level developments within.

None of the models discussed in this section are suitable for the macro adoption of DLT in construction as a standalone tool to achieve readiness either because they were developed for a different organisational scale (i.e. individual, organisation), for a different industry, or simply do not fit the requirements for DLT. While some elements are applicable under the right circumstances, a number of the steps in existing models are elementary and carry little meaning. Construction is complex and requires changes across many faces of the industry before acceptance and adoption of new innovations and systems can be successful. This has been shown through the challenges faced by BIM, therefore, a specific roadmap that addresses the industry's complexity and track record of technological advancement is required. The next section proposes the DLT Roadmap that was influenced by some of the models discussed here.

3. Proposed DLT Roadmap to achieve readiness for adoption of DLT in construction

The proposed DLT Roadmap is a continuation of the socio-technical framework offered in [4]. As DLT is yet to be adopted in the construction industry to any noticeable extent, the purpose of this roadmap is to support the industry with its itinerary toward implementation and adoption. A roadmap at this stage will provide a more streamlined approach to adoption of a new system allowing the industry the opportunity to have all supporting infrastructure in place prior to implementation; it allows time to educate users/beneficiaries of the new system about its benefits whilst highlighting any potential challenges they should prepare for; and it supports the development of industry standards and regulations [30]. As discussed earlier in this paper, adoption of DLT in construction needs to happen at the macro scale at this early stage. DLT is a collaborative system that requires adoption throughout the supply chain and throughout the asset lifecycle; individual or organisational adoption alone will not be sufficient for its success as this does not increase trust between contracting parties nor does it promote intra-organisational decentralisation.

Technology roadmaps provide "a comprehensive approach for strategy planning to integrate science/technological considerations into product and business aspects as well as to provide a way to identify new opportunities in achieving a desired objective from the development of new technologies" ([5], p. 690). The DLT Roadmap (Fig. 1) is designed to support the construction industry in its decision to adopt DLT through offering a robust sequential process that will support development of a new set of processes and policies and aid in preparation and planning for its implementation. The roadmap is designed to support implementation of DLT for specific use cases rather than DLT generally recognising that some will require more preparation and legislation and will involve different actors and activities than others before successful adoption can occur. It consists of four stages: 1 Conceptualisation, 2 Appraisal, 3 Preparation and 4 Implementation. *Conceptualisation* provides understanding of what value DLT can add for a specific use case; *appraisal* considers the current environment and what needs to change to allow for adoption of DLT for the selected use case; *preparation* puts measures in place to ensure implementation of DLT is a success; and *implementation* sees those measures realised successfully. It considers the construction industry's current and desired state with respect to DLT and proposes progressive activities for the industry to follow at each stage that will guide informed decisions to continue toward adoption or whether to reject the new system between stages. These decision gates, indicated by the diamonds between stages in Fig. 1 offer the industry a structured process and introduce formal points where the benefits of continuing in terms of time, cost, opportunity costs, likelihood of success and appetite for the new system are reviewed. It is recommended that an industry appointed task force be established early (i.e. by government) to drive this roadmap as in [27]. The task force should consist of participation from diverse groups within the industry (i.e. industry practitioners, government, academics) who should be available for the duration of the roadmap giving the benefit of early buy-in from the people tasked with implementation [25].

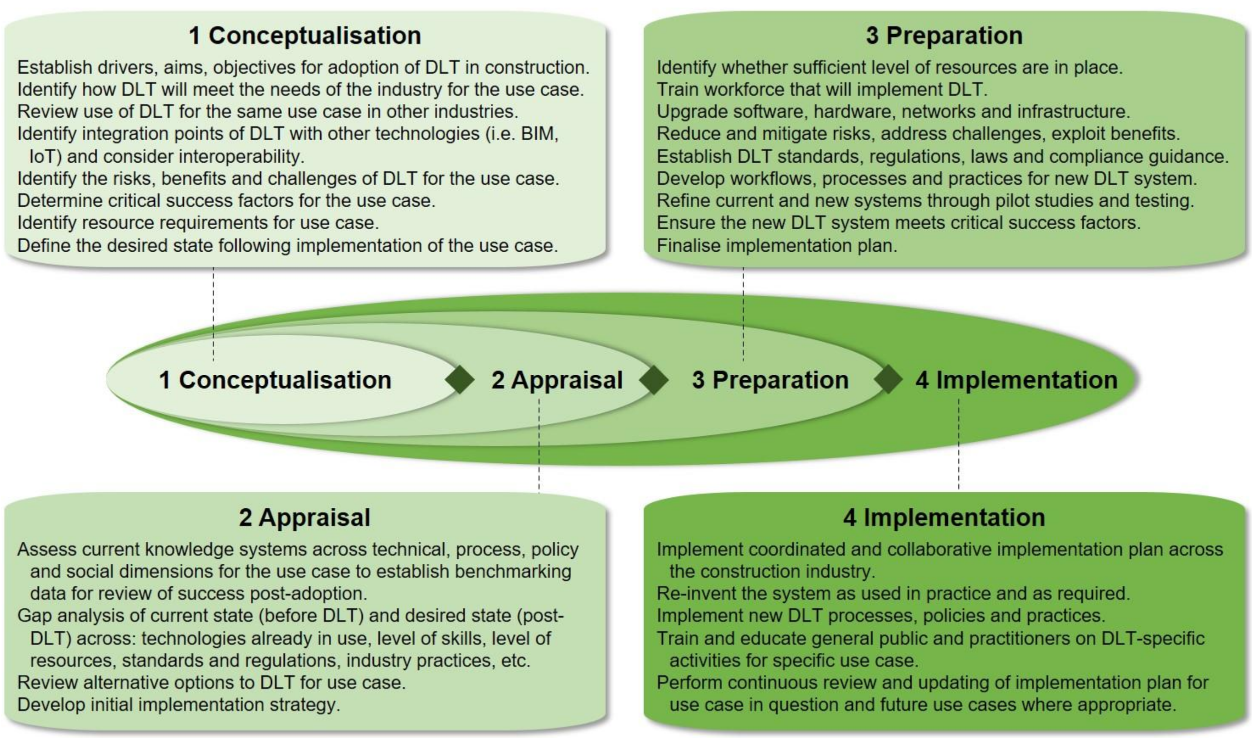

Fig. 1. DLT Roadmap

In further work, the four stages will be supported by a set of guiding components across the four dimensions (technical, process, policy, social) to for application to specific uses of DLT (i.e. automated supply chain payments, maintaining a historical digital record throughout the lifecycle of an asset). The four roadmap stages were devised from assimilating relevant aspects of existing models and roadmaps for adoption of new technologies as discussed in section 3.

Fig. 1 provides details of the proposed activities that should take place during each stage that will be adapted for different use cases. The ***conceptualisation*** stage directs the task group to gain a comprehensive understanding of the use of DLT as part of the solution through research into the feasibility of DLT for the use case across the industry by completing the activities. This will enable the task force to make a decision on whether to continue towards adoption or reject DLT for this use case. The ***appraisal*** stage provides understanding of the current state of the industry for the use case by comparing it against the desired state with adoption of DLT. This enables the task force to identify changes that need to be enacted during the preparation stage before implementation can take place as well as providing benchmarking data against which to compare post-implementation data to measure success. The decision to continue towards adoption or to reject the use of DLT for the use case is made based on the appraisal activities where the decision to continue leads to the ***preparation*** stage. Here the task force should ensure that everything required for successful implementation, as identified through the conceptualisation and appraisal stages, is in place and that changes are made where necessary such as developing and/or updating software and hardware required to adopt DLT for the use case and to enact legislation so the new system operates within the confines of the law closing any potential loopholes for criminal and/or fraudulent activity, particularly where finances are involved. Following the final decision to adopt DLT for the use case in question, the ***implementation*** stage commences where the implementation plan is executed. During this stage, the benefits identified at the conceptualisation stage, along with others identified throughout the process, will begin to be realised. Success can be measured against critical success factors and benchmarking data. Challenges and benefits not perceived until implementation will be identified and mitigated or exploited as the new system is re-invented to ensure it is fit-for-purpose. From the implementation stage onwards, the system will be continuously refined and updated as DLT advances and as new use cases emerge.

4. Discussion and conclusions

This paper proposes a four-stage DLT Roadmap to support macro adoption of distributed ledger technology in the construction industry adaptable for specific use cases. It aims to assist development of a set of robust processes and policies to create an ecosystem that will support its implementation into a complex industry. The four-stages in the DLT Roadmap (conceptualisation, appraisal, preparation and implementation) were developed through considering contributions of other readiness models and technology roadmaps used in similar industries as no roadmap exists for DLT in construction. Each stage consists of a number of activities to be conducted that build on one another to create the ecosystem needed for successful implementation of the system. It is a developmental process that will support an appointed task force from conceptualisation through to implementation with structured adopt/reject points at the transition from one stage to the next and prescribes continuous reviews and updates of the implementation plan as the system advances and more is learned about how it will integrate and be implemented across the construction industry. The DLT Roadmap was developed specifically for the construction industry; its novelty lies in its ability to be adapted for any use case in the construction industry considering that the ecosystem required for successful adoption of DLT will differ from use cases to use case. For example, financial payments via smart contracts will require enactment of new financial legislation, task automation that does not include a financial payment will not. This will be demonstrated in future research as the DLT Roadmap is applied to specific use cases.

The DLT Roadmap forms part of the socio-technical framework for DLT that consists of the DLT Four-Dimensional Model and the DLT Actors Model to represent flexible, adaptable and scalable knowledge constructs and foundations that can be used for various investigations related to DLT applications in construction. DLT has the potential to support solutions to many of the challenges the construction industry faces with regards trust, collaboration and information sharing, regulation and compliance, payments and more [4] but it needs to be nurtured carefully to avoid challenges such as those experienced by the adoption of BIM.

This study’s key limitation is that the DLT Roadmap was based on roadmaps developed for purposes other than DLT, some for individual or organisational application rather than industry-wide. There is the possibility that when the process is used in practice some elements will not meet the requirements needed for achieving readiness for adoption of the innovation. However, part of the roadmap is to review the process and update it based on real-world application.

The next phase of the research will involve the proposal of guidelines for each of the four dimensions and their associated components across the four stages of the DLT Roadmap and be validated with industry practitioners and academics. It will consider integration with other technologies (i.e. BIM, IoT and smart contracts) as well as incorporating aspects such as creation of plans to train the required skills and educate the general public about DLT. In addition, a number of workshops will be held to identify a series of use cases with industry practitioners, academics and government to demonstrate how the DLT Roadmap and guidelines can be employed in practice.

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Application of artificial intelligence to automate construction materials data classification

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Abstract

The applications of Big Data analytics and Artificial Intelligence (AI) have gained a widespread attention in the construction industry in recent years following the promulgation of Industry 4.0. In the realm of construction research, AI has been utilised widely in areas such as structural design optimization, resource and equipment planning, and project scheduling. The research presented in this paper is aimed to utilise AI to assist with the automatic classification of the large volume of construction material orders created by users through an online marketplace website. Such big data of material orders contained numerous errors (e.g. typographical errors and incorrect units) that were extremely time consuming to correct before the datasets can be used to for further business intelligence analysis. In this research, the dataset was obtained from a business-to-business e-commerce company in Thailand, namely BUILK. The data from BUILK was the construction materials purchase orders created by BUILK's customers through its website, which contained hundreds of thousand unorganized records. In this study, Artificial Neural Networks (ANNs (was applied to automate the categorization of approximately 220,000 records of reinforcement steels orders. The ANNs model was developed and trained using over 32,000 records, with approximately 92 percent of prediction accuracy. The model automatically categorized the steel reinforcement data into 11 groups; Deformed Bars, Round Bars, Wire mesh (Deformed Bars), Wire mesh (Round Bars), Stirrup, Anchor, Material and Others. The outcome of this research helped the company to easily analyze the data to generate insights for its business management and development.

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Keywords: artificial nearal network; big data; business intelligence; construction materials; purchase orders; Thailand

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1. Introduction

A number of small and medium sized contractors in Thailand has grown rapidly. More than 10,000 construction materials purchase orders per day were made by these contractors using tradition transaction systems that are difficult to manage and verify. In various construction projects, the cost of materials consists of approximately 50% to 60% of the total cost of each project [1]. Therefore, the better control of construction cost materials plays a significant role in the financial management of a construction project. In this case, an enterprise resource management system in a construction project becomes very essential to understand the usage and flow of construction materials in the project. In addition, having readily access to the supply of construction materials at the prices that are consistent with those estimated in the Bills of Quantities (BOQ) can further improve the project delivery to help decrease the risk in the construction business by streamlining the project supply chain. In Thailand, BUILK is a company that provides Software-as-a-Service (SaaS) for a business-to-business (B2B) e-commerce for the construction industry. The company offers an Enterprise Resource Planning (ERP) solution with recent electronic marketplace service that allows the contractors to easily procure construction materials and products directly from the suppliers. One of the most common services that customers use is creating an online purchase order (PO). Each PO consists of various construction materials or products requested by the contractors. Apart from fulfilling the customers' orders, some of these PO items (POIs) have useful business implications that BUILK can capitalize on. However, the value of data would not be fully exploited, if the construction material PO data are unorganized or contain many errors. Given the widespread applications of Big Data analytics and Artificial Intelligence (AI) in the construction industry in recent years, the research presented in this paper was aimed to apply AI to help organize and cleanse the large volume of PO data stored in BUILK database, using Artificial Neural Networks (ANNs). ANNs is a classification technique in machine learning applied to categorize the construction materials into each group through the extraction of specific words from the material descriptions [2]. The results from this research help the company to visualize their data to reveal interesting trends of material prices and insights into the construction market. In addition, BUILK could use the vast amount of such organized data to increase the efficiency of their electronic marketplace platform.

2. Material and methods

The aim of this research was primarily to apply ANNs to automatically categorize big data of material orders, which contained numerous errors (e.g. typographical errors and incorrect units) so the datasets can be used to for further business intelligence analysis. This was achieved using "Classification", which is a part of supervised learning technique in Machine Learning (ML). Particularly, "Text Classification Process" was employed to prepare the data set prior to being further processed through a model developed using ANNs. In doing so, words in the datasets were converted to numerical values and split into specific proportion of test and train subsets. ANN is a widely-used technique to solve classification problems. For this research, ANN was applied to classify unorganized reinforcement steel data set using the Keras library running on TensorFlow, which has been developed by Google for deployment and operation of large scale machine learning models. The Keras library allows users to easily create neural networks that can be used for deep learning purposes. The following sections provide more details of the abovementioned research tools.

2.1 Text Classification Process

Text Classification Process (Fig. 1) consists of the following steps [3]: (1) Conversion of the original text file into the CSV format and importing it to Python [4]; (2) Word tokenization - words were split into letters and stored in the so-called "bag-of-words", each labelled with a number (commonly known as "features") [5-7]; (3) Stemming - the removal of the misspelled words or words with the same stem and then retaining the stem or the most common of them as a feature. In this paper, stemming process was not used because letters were used instead of words; (4) Identifying "Stopwords" – repeated words or letters were removed in the bag of words to reduce the amount of features. In this research, the same letters were removed from the bag of words with only unique letters retained; (5) Vector representation of text – the predetermined construction material categories were labelled (called a labelled set) using a series of binary (0 or 1) vectors to represent the description of each category [8]; (6) Feature selection (or feature transforming) - the counting of how many times each unique letter occurred in the description of each construction material, and normalizing the frequency of each unique letter with respect to the length of the construction material description (i.e. the total number of letters appear in the description); (7) Machine learning algorithm development - ANNs was employed to develop a text classification algorithm.

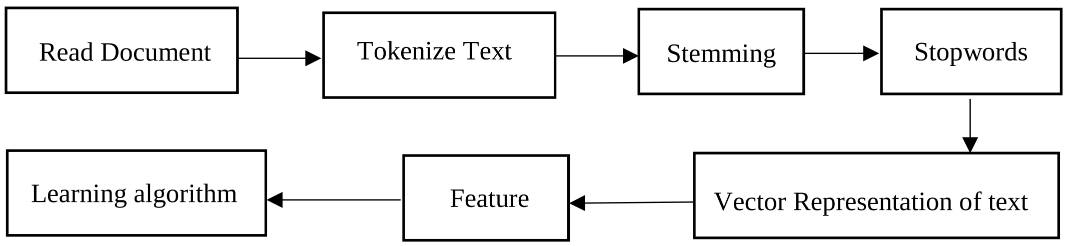

Fig. 1. Text Classification Process.

2.2 Data preparation for Text Classification Algorithm Development

The original data set of BUILK construction material descriptions was divided into train and test sets. The train and test sets were required in the development and measurement of the overall model performance of the text classification algorithm. Prior to the algorithm development, each of the 32,380 construction material descriptions in the original data set was manually grouped into 11 categories (activities, anchor, deformedbar, material, roundbar, screw, steel tube, stirrup, wiremesh deformedbar, wiremesh roundbar and other). Table 1 shows an example of the 11 construction material categories for the selected material descriptions [9]. Each category was then converted to numerical values shown in Table 2. These categorized datasets were then used in the subsequent development of ANNs-based text classification algorithm.

Table 1. Construction material dictionary.

Construction Material Description	Categories
ค่าขนส่งเหล็ก	activities
พุกเหล็ก 1/2	anchor
เหล็กข้ออ้อย 6 มม. SD-40 12 มม.*10 ม. โรงใหญ่ (พับ/ตรง)	deformedbar_db
ใบตัดเหล็ก Dwalt 4" หนา 1 MM	material
ชอล์คหินขีดเหล็ก	other
เหล็กเส้นกลม 6 มม SR 24*10 ม บกส	roundbar_rb
สกรูยึดโครงเหล็ก	screw
เหล็กกล่อง 1*1	steel_tube
เหล็กปลอก 20 x 65 (RB 9)	stirrup
ตะแกรงเหล็กข้ออ้อย 6.0 มิล 15x15 (3.0x4.0)	wiremesh_db
เหล็กตะแกรงไวร์เมชกลม 4.00 m @ 20 x 20 cm. ขนาด 2.50 x5.0 m	wiremesh_rb

Table 2. Construction material categories

Key	Type	Size	Value	Vector
other	int	1	0	[1,0,0,0,0,0,0,0,0,0,0]
deformedbar_db	int	1	1	[0,1,0,0,0,0,0,0,0,0,0]
material	int	1	2	[0,0,1,0,0,0,0,0,0,0,0]
roundbar_rb	int	1	3	[0,0,0,1,0,0,0,0,0,0,0]
activities	int	1	4	[0,0,0,0,1,0,0,0,0,0,0]
steel_tube	int	1	5	[0,0,0,0,0,1,0,0,0,0,0]
screw	int	1	6	[0,0,0,0,0,0,1,0,0,0,0]
anchor	int	1	7	[0,0,0,0,0,0,0,1,0,0,0]
stirrup	int	1	8	[0,0,0,0,0,0,0,0,1,0,0]
wiremesh_rb	int	1	9	[0,0,0,0,0,0,0,0,0,1,0]
wiremesh_db	int	1	10	[0,0,0,0,0,0,0,0,0,0,1]

.23 Artificial Neural Networks

Artificial Neural Networks or ANNs are widely used for performing functions related to learning, classification, relating, determination specialty, generalization and optimization similar to those performed by a human brain [10]. In the construction industry, ANNs can be used for classification of information such as construction materials, types, and suppliers. The muti-layer perceptron (MLP), which is the most common type of ANN, was used in this research to model the potentially nonlinear response of the unorganized construction material description data. The MLP is a collection of connected processing elements called nodes or neurons, arranged together in three layers: input layer, hidden layer (intermediate) and output layer [11]. The raw data in the MLP neural network is normalized and fed into the input layer. It is then passed into to the hidden layer and subsequently into the output layer as shown in Fig.2.

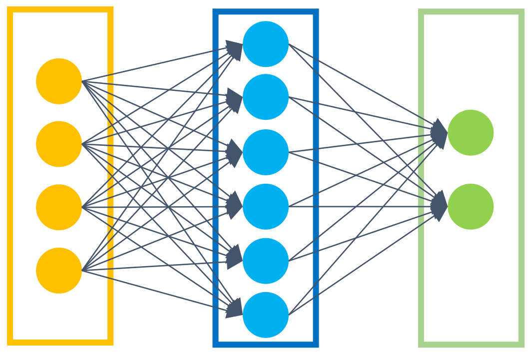

Fig. 2. Diagram of a multilayer feed forward neural network.

For this research, the input layer consists of 196 unique letters extracted from the material descriptions as carried out in the feature selection (feature transformation) process explained in Section 2.1. The output layer consists of the 11 construction material categories stored in binary vectors (Table 2). The datasets were divided into train and test sets based on the ratio of 70:30 [12]. The 70% data portion was trained using the Keras framework in TensorFlow [13]. The results of the ANNs is determined by the nature of its activation function. Activation functions are an extremely important feature of the ANNs. They decide whether a neuron should be activated or not, i.e. whether the information that the neuron is receiving is relevant for the given information or should it be ignored. It is the non-linear transformation that is performed over the input signal. This transformed output is then moved to the next layer of neurons as input. In this paper, Rectified Linear Unit (ReLU) and SoftMax are the commonly used activation functions that were used in the developed model [14, 15].

3. Results and discussion

As summarized in Table 3, the result showed that the developed model (based on the original datasets of 32,380 construction material records) was able to achieve the training cross validation and test accuracy values of more than 90%. In particular, the model achieved the following test accuracy metrics: Precision 0.92, Recall 0.90, and F1-score 0.91. Table 4 shows the reduction in losses and increase in percentage of accuracy across a 10-fold training cross validation. These results indicate that the developed model is of acceptable performance.

Table 3. Accuracy metrics

Metrics / Models	ANNs Model
Training cross validation	≈ 98%
Test accuracy	92.33%
Precision	0.92
Recall	0.90
F1-score	0.91

Table 4. Training accuracies and losses per fold in 10-fold training cross validation

Fold #	Loss	Accuracy (x100%)
1	0.5078	0.8434
2	0.2371	0.9231
3	0.1754	0.9416
4	0.1332	0.9568
5	0.1009	0.9672
6	0.0809	0.9748
7	0.0658	0.9797
8	0.0500	0.9852
9	0.0431	0.9870
10	0.0359	0.9896

The predictive performance of the developed ANNs model was then tested using the Confusion Matrix, which shows how well the predicted value match with the true value as indicated by the intensity of the color of the squares alinging diagonally across the matrix. As shown in Fig. 3, the ANNs model had the high number of correct predictions as indicated by the high intensity of the color of the squares.

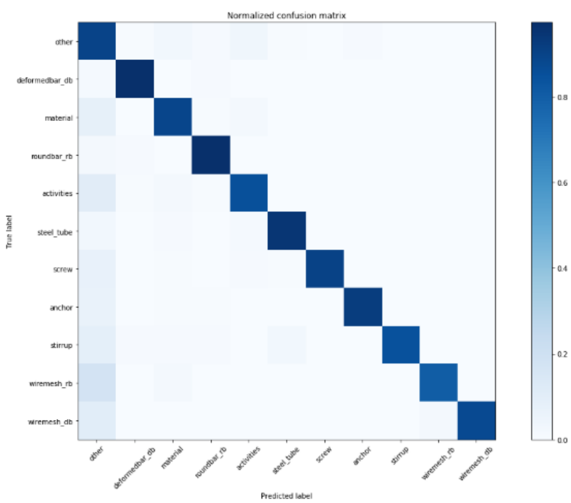

Fig. 3. Normalized confusion matrix of the construction materials labelled

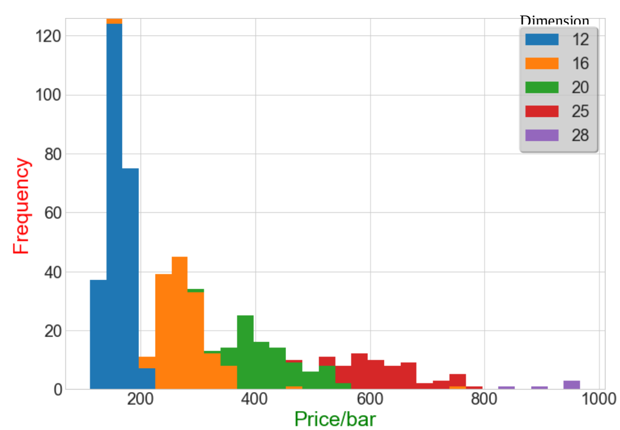

Fig. 4. Deformed Bar priced comparing in various dimension.

The applicability of the developed model was then tested using the new dataset obtained from the company. This new dataset consisted of approximately 220,000 records of purchase orders. The model was applied to categorise the reinforcement steel bars (rebars) into 11 categories. For the company, this model has a benefit in assisting the business analyst to quickly organize the large volume of purchase orders data in order to help extract some insights for their business. For example, as shown in Fig. 4, the results of the categorisation can be used to illustrate the prices and demand of steel rebars across different diameters. This type of information can help the analyst to quickly understand the price distributions of steel rebars based on different sizings. Addition analysis of the categorized data may help reveal other important information such as the price fluctuation of rebars across different region at different time points.

4. Conclusion

The research presented in this paper demonstrates a business application of AI in the construction industry apart from the technical application such as in areas such as structural design optimization, resource and equipment planning, and project scheduling. In this research, AI was applied using ANNs-based text classification technique to automate the

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categorization of unorganized big data of construction material orders. The ANNs model was developed using the actual purchase order data from the construction e-commerce company in Thailand, namely BUILK. The was developed and tested using the data of 32,380 construction material purchase order records. The developed model demonstrated an acceptable performance and was subsequent used to automatically categorize the larger set of 220,000 records of purchase orders. Such model helped the company to easily organize and analyze the data to generate insights for its business management and development. The future application of such model could also further benefit the online construction material searching service of BUILK whereby the model could make search recommendation to users in the same way as that seen in Google Search Engine.

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Architecture of dispersed multilayered cyber-physical robotic system for coordination of manipulating robotic system using UAV

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Abstract

Drone technology has demonstrated to be of great contribution to the construction field. Tasks such as photogrammetry, plot surveillance and assets inspections are successfully automated with the aerial robotic technology with some level of contribution of a human operator. In this paper we analyze the possibility to achieve fully automated construction task using dispersed robotic system: a drone and mobile robotic crane. The role of the drone is to study the surroundings and generate a desired trajectory for the crane boom arm in order to lay-in pergola blades. The paper focuses on the layers of the dispersed cyber-physical system allowing to achieve such complex task and optimize the trajectory of the crane boom arm by resolving two-dimensional Chebyshev-Gauss collocation method in order to have minimum-jerk path.

Keywords: cyber-physical system; drone; trajectory generation; robotics in construction

1. Introduction

The practical implementation of the cyber-physical systems in our day to day life is well established. We recognize the development in such solutions leading to Internet of Things (IoT), augmented and virtual reality contributing to a new level of end-user's satisfactions and extended useful experience. In contrast, the paradigm of applying cyber-physical systems to the construction field is yet to explore and set its own potential. This is majorly due to the late and slow development of the autonomous and robotized platforms which has a projected application in the construction field.

A techno-commercial solution of the autonomous systems in construction is rarely considered as it is always cheaper and less risky to deploy man-power (carpenters, steel fixers) rather than purchasing and customizing a robotic solution. In one hand, the implementation of sophisticated solution is costly and require specialized staff present at site for monitoring, and on the other hand, the solution is not widely tested and its results are barely registered and recognized.

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In this paper, we tackle the first challenge aiming to reduce the specialized and idle man power by studying the automation level required to lay-in pergola blades on top of a building using dispersed cyber-physical system composed of a drone and a mobile lifting crane. By cyber-physical system, we understand the concept of reliable fusion between computational and physical platform embedded within the same body [1], however, enabling better interaction capabilities with the surrounding (world and human operator) though many modalities and processes. In light of that, the terms of interaction, integration and enhancement are key areas where the research of cyber physical systems is occurring.

Traditionally, the physical system is a consolidated system and not dispersed over selected area. Recently, with the introduction of Internet of things, the probability of designing distributed physical systems became achievable, as it overcame the disadvantages of radio systems and the huge cost related to GPS and GLONASS integration in navigation platforms, which made this solution not optimal techno-commercially. In this paper, we introduce the cyber-physical system consisting of the following levels:

- Aerial: a UAV scanning the roof and generating the positioning tasks for the subsequent component of the pergola;
- Cybernetic: analyzing the video-input of the UAV and generating trajectory for the manipulator using visual odometry algorithm;
- Ground: a Mobile robotic crane, receiving the coordinates from the cyber system and performing the laying-out of the pergola blades.

A concept of the solution is illustrated in fig.1 according to which, the UAV will dictate the following parameters as a potential control task to the cybernetic system: the swing angle ϕ, the luff angle θ, the hoist elevation h and the mobility across axis OX and OY, which can be replaced by the angle formed by the hoist and the luff axis [2].

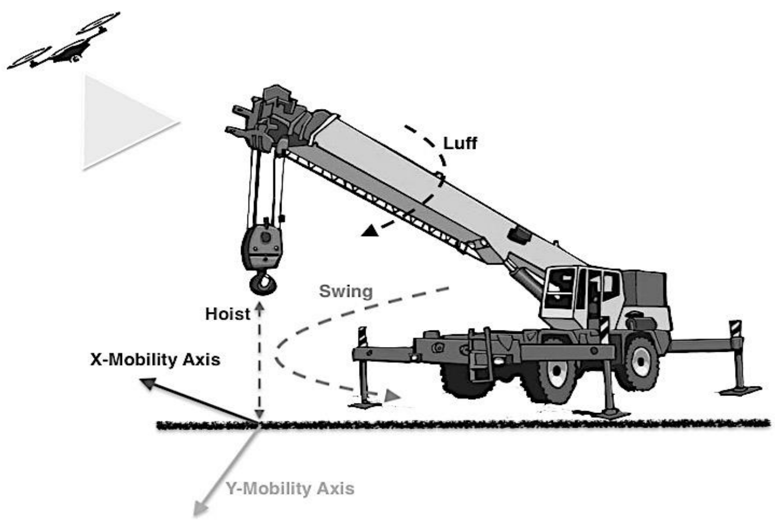

Fig 1. Concept of dispersed cyber-physical system

2. Paradigm of Proposed Cyber Physical System

By paradigm, we underline a worldview underlying theories and methodologies of a particular scientific subject. To some extent, the notion of the cyber-physical system is well defined in the IT fields. However, its application in other engineering subjects is yet to be defined. Our target in this paper is to make notions more tangible and hence allowing better evaluation and optimization. In line of that, we will be studying the generic system architecture, the enabling knowledge and technology assets, and distinguishing system characteristics allowing for expansion and optimization.

Cyber physical systems (CPS) have emerged from the synergetic merging of information, sensory and communication system with a physical system. This is a comparable notion to mechatronic system, from where we will begin integrating CPS architecture to the electromechanical word of construction. In addition, we have to consider the human-machine interface as the CPS will not be deployed at site in isolation with the other construction activities. Hence, an additional layer in the CPS will be figuring out and influencing on the overall performance of the system. Fig.2 illustrate generalized CPS layers and compared to the applied proposed CPS [6,7].

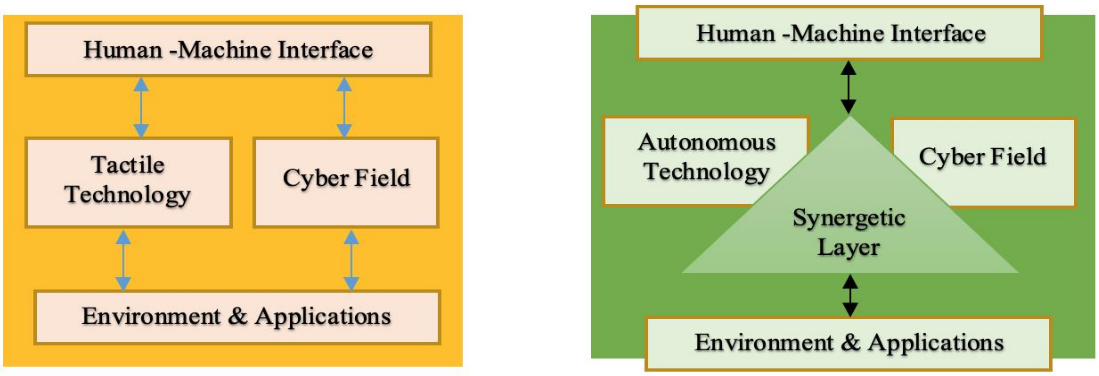

Fig 2. Traditional and Proposed CPS

As it can be seen from fig.2, the difference between a traditional and the proposed CPS can be highlighted in several points: firstly, the human-machine interface is encompassed inside the CPS in the traditional system, however, in the proposed layout, the layer is peripheral and has no direct interaction with the autonomous technology and cyber field. Secondly, the tactile technology is substituted with an autonomous system as we are aiming to robotize construction task and lastly, the direct interaction with the environment and application is done by a synergetic "mechatronic layer" responsible of communication and execution of the task. In addition, the environment layer is neither connected directly to the autonomous and cyber system. In short, the difference lays in omitting the human factor influencing the process and replacing it with actuating mechanism.

The proposed model complies with the worldwide notions of CPS especially point C5 stating the system should be articulated and heterogenous. By articulated, we define the connectivity of the system with its embedded components and environment; and by heterogenous- we mean the different physical origin of each systems: having a cyber part, a synergy and actuators. The same is import as the CPS can suffer possible downtime leading to task failure. In this case, the CPS analysed by its Cyber part has to plan for a functional (graceful) degradation [3].

3. System Architecture

In this paragraph, we will discuss the core parts of the CPS, its parameters, requirement and functions. We will study the cyber system component, set the algorithm of trajectory generation for the crane boom arms using UAV and identify the transformation equations between the pixel and metric references. The last part of the paragraph will address the optimization of the generated trajectory and transformation of the boom arm movement to a two-dimensional Chebyshev-Gauss collocation method in order to achieve minimum jerk movement considering zero initial conditions.

3.1. Cyber system

Firstly, regarding the cyber field, an embedded software command the generation of the trajectory of the crane boom arms and requirement of the geometric coordinates explained in paragraph1. In addition, the cyber system is responsible of intra and inter-objects transmissions. As per the current standards of CPS the following range of transmission for a multi-scale CPS need to be identified:

Tab.1 Transmission Range for Intra and Inter-Objects communication

Intra-Object Transmission		Inter -Objects Transmission	
Not Available		Global	10^6m
Nano Scale	from 10^{-9}m	Long range	10^4m
Micro Scale	Up to 10^{-6}m	Medium Range	10^2m
Macro Scale	Up to 10^{-3}m	Short Range	10^0m

From tab.1, we need to pay attention to the following: the intra-object transmission needs to be respected and achieved by all means, since it is a mandatory requirement for possible functional degradation in case of system failure. Pertaining to the inter-objects' transmission, a least of medium range should be achieved allowing the communication between the drone and the crane with possible engagement from the human-machine interface.

The other part of the cyber system is the trajectory generating software. We will be deploying the drone, equipped with a camera, to generate desired trajectory for the boom arm, study possible collision and assign subsequent step to lay the pergola blade. Using machine vision and odometry, CPS can autonomously define the trajectory of the boom arm. Figure 3 and equations (1-3) illustrate the transition between pixel to metric coordinates.

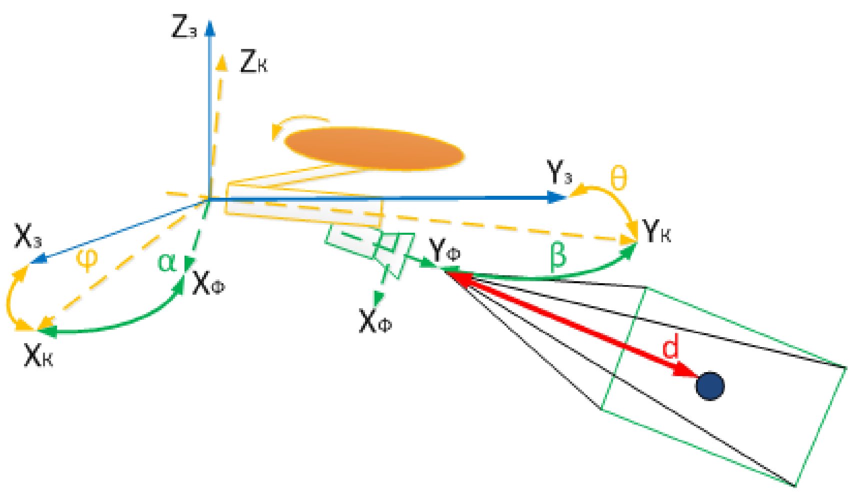

Fig 3. Illustration of different reference systems and coordinates

The distance from the camera to a specific coordinate (Earth-axis) is computed using the following equations:

$$d(x) = H_{\text{г}} = H * \tan(\varphi + \alpha); \quad (1)$$

$$d(y) = H_{\text{В}} = H * \tan(\theta + \beta), \quad (2)$$

Using equations (7) and (8), we can identify the transformation formulas between different reference systems.

$$\begin{cases} X_{\text{п}} = \frac{x}{\Pi x} . \cos\left(\arctan\left(\frac{H_B}{H_{\text{г}}}\right)\right) \\ Y_{\text{п}} = \frac{y}{\Pi y} \sin\left(\arctan\left(\frac{H_B}{H_{\text{г}}}\right)\right) \\ \rho_x = \sqrt{X_{\text{п}}{}^2 + Y_{\text{п}}{}^2} * cos(\arctan\left(\frac{H_B}{H_{\text{г}}}\right)) \\ \rho_y = \sqrt{X_{\text{п}}{}^2 + Y_{\text{п}}{}^2} * sin(\arctan\left(\frac{H_B}{H_{\text{г}}}\right)) \end{cases} \quad (3)$$

Where $X_п$ and $Y_п$ − are the pixel coordinates, x and y − are the body axis coordinate and ρ_x and ρ_y are the angular pixel coordinates.

3.2. Actuating System

The actuators are responsible of fulfilling the generated trajectory, to lift and lay the pergola blades according to the defined coordinates. In addition, the process has to be jerk-free movement in order to avoid collisions and inverted pendulum effect, especially that wind might affect the positioning of the blade at a certain height. To achieve an optimal trajectory to the manipulator, the movement will be posed and solved as quadratic programming using multi-segment Chebyshev orthogonal collocation for transcription. Using the two-dimensional Chebyshev-Gauss collocation method to obtain possible numerical solution of differential equation by partially is differentiating it in time and discretizing it using finite difference method [4]. Taking into consideration that the trial or candidate trajectories $f_k(x)$ will be set on homogenous Dirichlet boundary conditions [3], the approximate solution can be presented in the following equation

$$U^N(x,t) = \sum_{k=0}^{N} a_k(t)\, f_k(x) \tag{4}$$

In the collocation approach, the differential equation has to be satisfied by the approximate solution at the collocation points in the assigned domain [5]. The derivative at each node can be found by multiplying the value at any Chebyshev point by a differentiation matrix.

4. Results

By implementing the proposed model, and running the quadratic programming listing on Matlab, we obtained the result of multi-segment trajectory simulation as depicted in figure 4.

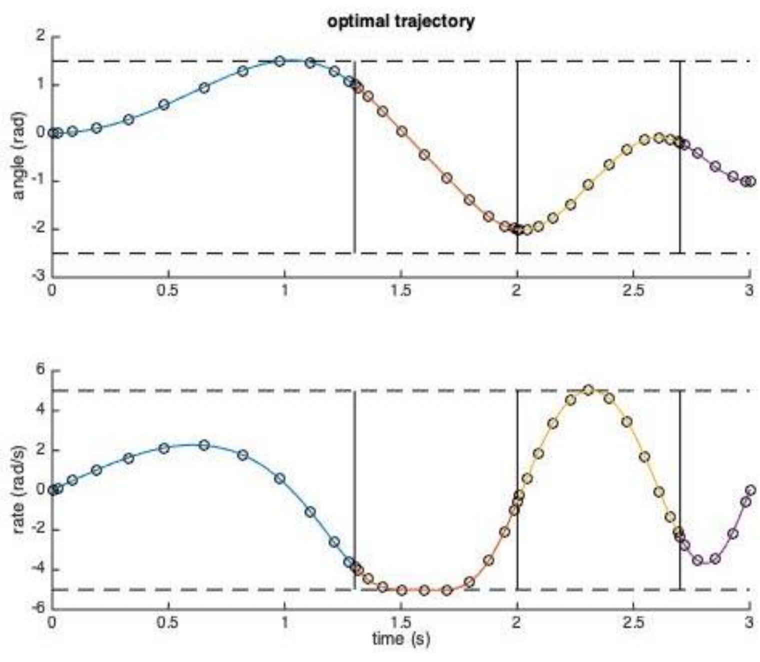

Fig. 4. Results of multi-segment trajectory

In figure 4, we can clearly see, that the trajectory is passing by all the Chebyshev node points, where the initial a final velocity rated in rad/s is zero and the angle of the final trajectory is almost negligible.

By applying the same concept to the both sections of the manipulator, with specific boundaries and input trajectory, we can see that the arm end-effector holding the bald is travelling smoothly, on the doted lines, shown in fig.5, taking into consideration for joint 1 and 2, the initial velocity is zero (starting point of lifting task), and the resultant final velocity of the end-effector is also zero rad/s, which corresponds to discharge of the manipulator after laying task.

5. Conclusion

This paper studied the architecture of multilayered cyber-physical system consisting of UAV and robotic crane. The role of the UAV is to generate desired path for the crane boom arm in order to lift and lay pergola blades on top of a building. The paper addressed different layers of the cyber physical systems and proposed an additional synergetic part interacting solely with human machine interface and aquire information for the environment. In such scenario the cyber physical system will be bordered and allow for better functional (graceful) degradation if required. Later, the paper focused on the trajectory planning and generation of transportation coordinates of the pergola blades. The problem is

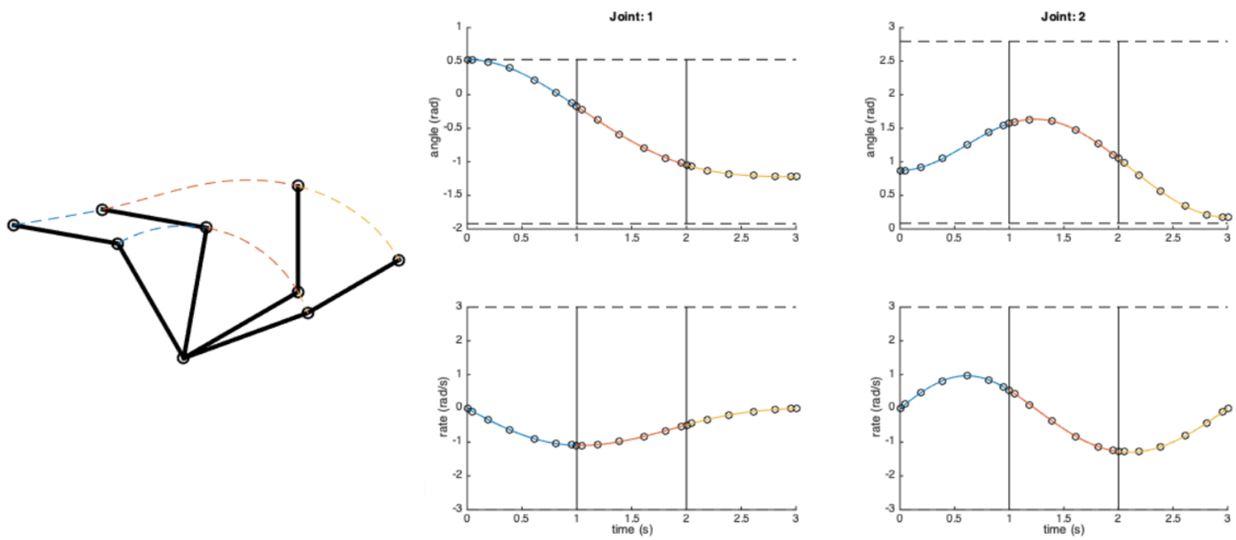

Fig 5. Minimum-Jerk Trajectory of the robotic manipulator corresponding to Chebyshev nodes

then transformed as two-dimensional Chebyshev-Gauss orthogonal collocation method aiming to achieve jerk-free transportation and positioning of the blades. The obtained simulation results illustrated both the joints of the lifting crane have followed the optimal trajectory, passing by all Chebyshev points with minimum jerk considering that the initial velocity of the joints is zero and the final velocity should be obtained zero rad/s with minimum to zero overshooting angles.

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Conceptual design of controllers for automated modular construction machines

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Abstract

Without a methodology, the practice of control system design for automated modular construction machines mainly depends on experience and trial-and-error. Implementation of controllers requires planning at the conceptual design phase. Axiomatic design (AD) has been introduced in developing control solutions. This paper formalizes the conceptual design methodology in building a controller with the use of quality function deployment (QFD) as a design and an analysis tool. The controller design approach using QFD has been applied to the automated steel wall framing machine and to a 2-degree-of-freedom (DOF) robotic arm, which can be readily extended to n-DOF robotic manipulators. The analysis and decoupling techniques for controller design presented in this paper differ from those used in traditional AD. QFD for controller design provides continuous transfer functions to represent relationships and mathematical decoupling that is easily implemented in software.

Keywords: controller design; decoupling; modular construction; quality function deployment; robotic manipulators

1. Introduction

Automation in construction arises due to the performance limitations of conventional construction [1] (Systems that realize the automation are, however, complex. An automated steel wall framing machine [2], for example, consists of mechanical, electrical, and control systems. Difficulties associated with designing an automated system can be overcome by the use of model-based system engineering (MBSE) methodology [3]. MBSE methodologies can be categorized as graphical or matrix-based. When adopted during the conceptual design phase, the matrix-based methodology provides a visual, compact, systematic, and transdisciplinary integrated MBSE approach [2].

To correct the usual practices in machine control system design that depend on experience and trial-and-error, Lee et al. [4] have illustrated the applicability of axiomatic design in developing control solutions. These authors have not employed QFD and process control decoupling techniques. QFD is a tool to align product design with customer needs [5]. A sequence of QFDs has been applied from customer needs identification, product planning, part planning, process planning and production control [6], which depicts the usefulness of QFD as a design and an analysis tool. Although not specifically called QFD, Lahiri [7] has applied the methodology only to develop a step test plan in the form of an

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expectation matrix for modelling a multivariable process. A formalized conceptual design methodology is still required in designing a controller.

This paper focuses on the use of the QFD matrix at the AD and DSM stages of the integrated conceptual design MBSE approach and is structured as follows. Section 2 describes the QFD matrix for controller design. Section 3 illustrates the applications of the controller design methodology. A discussion of results is discussed in Section 4 followed by the conclusion in Section 5.

2. Conceptual design of controllers

An integrated MBSE methodology involves the repeated use of quality function model (QFD) throughout the stages of conceptual design, namely: (a) customer requirements definition; and (b) integrate function modelling (IFM) development with the use of axiomatic design (AD) and design structure matrix (DSM). Fig. 1 depicts the multiple applications of QFD, which establishes a model-based conceptual design approach. In this figure, the controller design extracted from AD and DSM is represented as a QFD matrix, in P-canonical or V-canonical form, that dynamically relates the manipulated variables (MV) and control variables (CV) through continuous or discrete transfer functions. Two QFD matrices are required to fully represent a V-canonical structure and to properly apply a corresponding decoupling strategy. In following the traditional representation, it could have been more appropriate to show only one QFD with its roof comprising the CV correlation matrix. However, two matrices are used to emphasize the AD and DSM steps in the conceptual design of a controller as well. This QFD representation in the design of multivariable predictive controllers is called expectation matrix [7]. Inside the IFM is a collection of QFD matrices that constitutes the state, process/use case, actors, and interaction views. For the electrical control panel, the conceptual design method introduced in a study by Tamayo et al. [8] facilitates the subsequent computer-aided design to be performed at the detailed design stage. Controller QFD will be shown to have numeric, Boolean, and transfer function representations depending on the type of systems being developed.

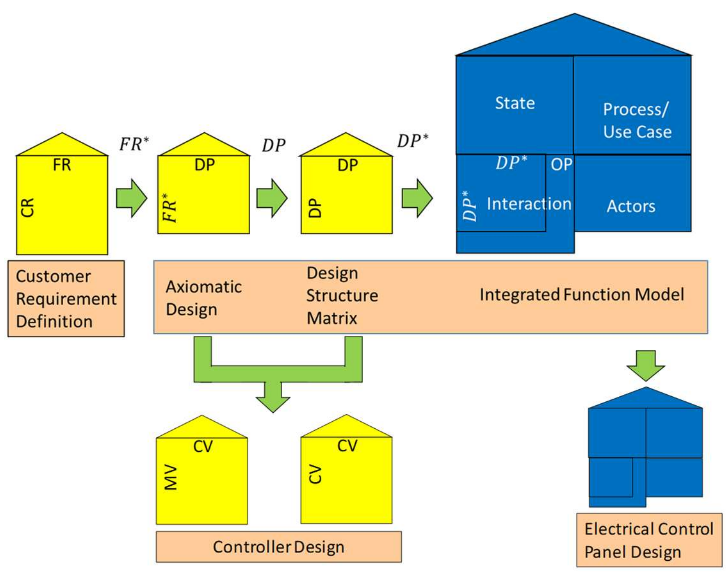

Fig. 1. Integrated conceptual design overview

2.1. QFD structures for controller design

As depicted in Fig. 1, a QFD matrix for controller design is extracted from the overall design matrix (DM) and DSM for the following reasons: *(i)* to express interactions in Laplace transfer functions; *(ii)* to identify coupled interactions; *(iii)* to design decouplers in enabling the designers to treat the control problem as loops consisting of independent systems; and *(iv*) to facilitate simulation at the conceptual design phase. Although controllers are not implemented in Laplace transfer functions, this QFD representation effectively communicates the behavior of the multivariable process.

Fig.2 illustrates a 2×2 multivariable process with its corresponding QFD matrix in P-canonical and V-canonical forms [9]. As in AD, coupling is shown as the off-diagonal elements of the matrix in terms of Laplace transfer functions. A completely decoupled system is desired since it allows designers to implement multiple single-input-single-output (SISO) controllers. A decoupling strategy that is appropriate for each canonical structure is discussed further in the next section.

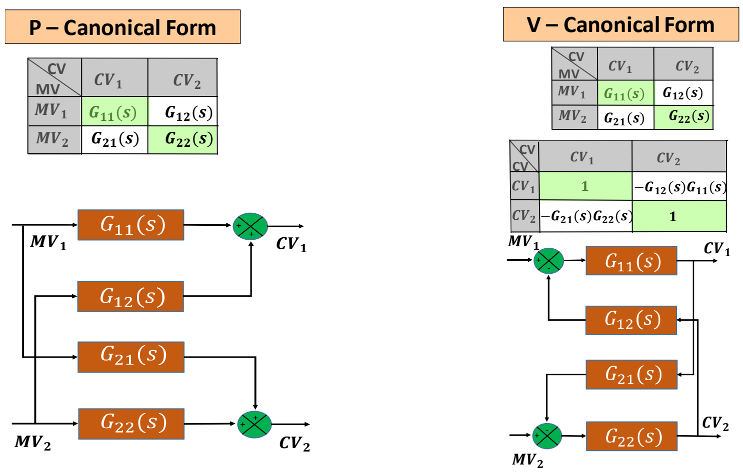

Fig. 2. QFD representations of a coupled 2×2 multivariable system

2.2. Decoupling strategy for P-canonical form

In this section, the decoupling techniques derived for 2×2 multivariable systems are easily extended to $n \times n$ multiple-input-multiple-output (MIMO) systems. It must be noted that a V-canonical form has an equivalent higher order P-canonical structure [9]. For simplicity, a V-canonical form is considered separately to avoid dealing with higher order transfer functions. A MIMO system of the P-canonical structure is expressed in the following equations:

$$CV_1(s) = G_{11}(s)MV_1(s) + G_{12}(s)MV_2(s) \tag{1}$$

$$CV_2(s) = G_{22}(s)MV_2(s) + G_{21}(s)MV_1(s) \tag{2}$$

Fig. 3 depicts a decoupling technique, with multi-loop PID feedback controllers, for the P-canonical structure that implements a diagonalization process in the following equation:

$$Q(s)G(s) = W(s) \tag{3}$$

where the decoupling transfer matrix, *Q(s)*, is chosen such that *W(s)* is diagonal. Eq. 1 has multiple solutions, but the simplest solution takes $Q_{11}(s) = Q_{22}(s) = 1$. In this case, $Q_{12}(s)$ and $Q_{21}(s)$ are then determined as follows (Marlin 2015):

$$Q_{12}(s) = -\frac{G_{12}(s)}{G_{11}(s)} \tag{4}$$

$$Q_{21}(s) = -\frac{G_{21}(s)}{G_{22}(s)} \tag{5}$$

Thus, for the general MIMO case, the decoupling transfer matrix can be expressed as follows:

$$Q_{ij}(s) = -\frac{G_{ij}(s)}{G_{ii}(s)}, \quad i, j = 1 \ldots n \tag{6}$$

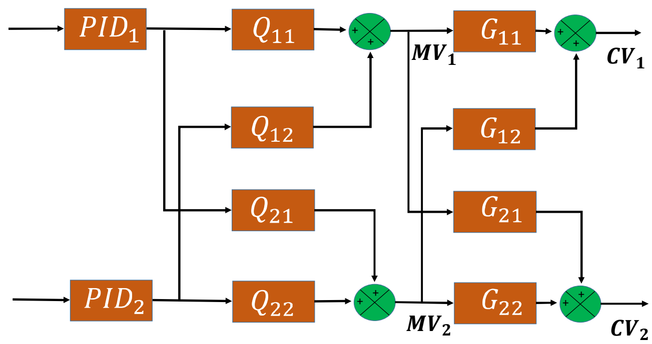

Fig. 3. Decoupling technique for a P-canonical MIMO system with PID controllers

2.3. Decoupling strategy for V-canonical form

A V-canonical structure is encountered in MIMO processes involving the following model, where the transfer function matrix, $G(s) \in C^{n\times n}$:

$$CV(s) = G(s)MV(s) \tag{7}$$

A model reference approach to decoupling requires that the output follow the reference command signal, which implies obtaining a feedforward controller, $Q(s) = G(s)^{-1}$, since

$$\begin{aligned} CV(s) &= Q(s)G(s)\, CV_{ref}(s) \\ &= CV_{ref}(s) \end{aligned} \tag{8}$$

Eq. 9 defines a feedforward controller that is the inverse of the process. This observation suggests using the linear or non-linear dynamic model of the process for decoupling by simply feeding the appropriate reference signals to the feedforward controller and augmenting its output to that of the feedback controller.

Thus, for the 2×2 MIMO system in Fig. 4, the feedforward controllers are**:**

$$Q_1(s) = CV_{1ref}(s)G_{11}(s)^{-1} + G_{12}(s)CV_{2ref}(s) \tag{9}$$

$$Q_2(s) = CV_{1ref}(s)G_{22}(s)^{-1} + G_{21}(s)CV_{2ref}(s) \tag{10}$$

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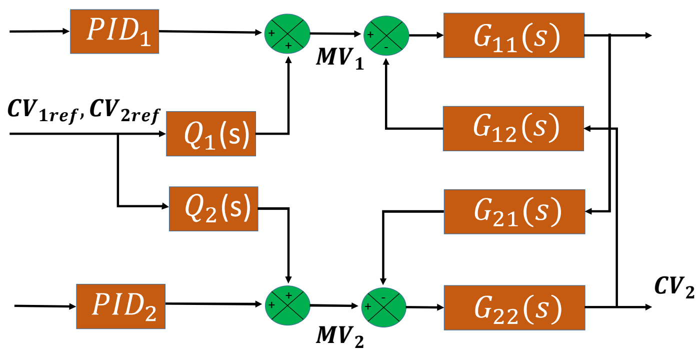

Fig. 4. Decoupling technique for a V-canonical MIMO system with PID controllers

3. Illustrative examples

3.1. Steel wall framing machine

An automated steel wall framing machine is illustrated in Fig. 5. This machine is capable of making three types of wall panels, namely: *(i)* with studs only; *(ii)* with studs and window; and *(iii)* with studs and door. Screw fastening is accomplished by first manually preparing the frames for automatic fastening, then entering the appropriate database for the frame being manufactured, and finally initiating the automatic screw fastening process.


Fig. 5. Automated steel wall framing machine

Features of the machine includes two power screwdrivers on the top gantry and two on the bottom gantry. To accommodate different widths of wall panels, one side of the table is positioned accordingly. Each dragging device is positioned at a right angle to ensure that the panel is square. Thus, the QFD matrix for control design depicted in Table 1 is developed using the functional requirements (FRs) extracted at the AD phase of the integrated conceptual design, and then observing that none of the motors are linked. Since movements are accomplished using stepper motors, the MVs and CVs in the QFD table are torques and distances, respectively.

Table 1. QFD matrix for the steel wall framing machine controllers

		CV_1	CV_2	CV_3	CV_4	CV_5	CV_6
Table	MV_1	X					
Clamp	MV_2		X				
Dragging	MV_3			X			
Y-axis position	MV_4				X		
Z-axis position	MV_5					X	
Fastening	MV_6						X

It is clear from the QFD matrix that the positioning control systems are uncoupled, indicating that each motor can be controlled individually, and that closed-loop stepper motors can be considered to simplify controller implementation.

3.2. Two link planar robotic arm

3.3. Robotic manipulators are coupled since the angular position of a motor in a joint affects those in the other joints. To illustrate the use of the QFD controller design described in the previous sections, a 2-DOF PUMA 560 robotic arm [10] is then discussed.

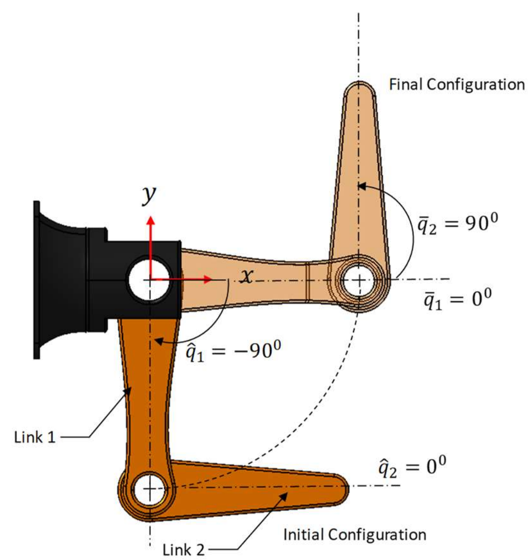

Fig. 6. 2-DOF robotic arm

Torque, $\tau \in R^2$, is dynamically related to the joint angle, $q \in R^2$, for the 2-DOF robotic arm shown in Fig. 6 as follows (Craig 2005):

$$\tau = M(q)\ddot{q} + V(q,\dot{q}) + G(q) \quad (11)$$

where for the masses and lengths of the first and second link as respectively m_1, m_2, l_1, and l_2, the following mass matrix, $M(q)$, centrifugal and Coriolis matrix, $V(q,\dot{q})$, and gravity matrix, $G(q)$, are obtained.

$$M(q) = \begin{bmatrix} {l_2}^2{m_2}^2 + 2l_1l_2m_2cosq_2 + {l_1}^2(m_1+m_2) & {l_2}^2{m_2}^2 + l_1l_2m_2cosq_2 \\ {l_2}^2{m_2}^2 + l_1l_2m_2cosq_2 & {l_2}^2{m_2}^2 \end{bmatrix} \quad (12)$$

$$V(q,\dot{q}) \ = \begin{bmatrix} -m_2 l_1 l_2 sinq_2 \dot{q}_2{}^2 - 2 l_1 l_2 m_2 sinq_2 \ddot{q}_2 \\ l_1 l_2 m_2 sinq_2 \dot{q}_1{}^2 \end{bmatrix} \tag{13}$$

$$G(q) \ = \begin{bmatrix} m_2 l_2 gcos(q_1+q_2) + (m_1+m_2) l_1 gcosq_1 \\ m_2 l_2 gcos(q_1+q_2) \end{bmatrix} \tag{14}$$

Using the example in (Seraji 1987), Eq. 7 is linearized at the operating point $\left[\bar{q}_1, \bar{\dot{q}}_1; \bar{q}_2, \bar{\dot{q}}_2\right] = [-\frac{\pi}{2}, 0; 0,0]$ to obtain the following equation.

$$\tau \ = A\ddot{q} + B\dot{q} + Cq \tag{15}$$

For the PUMA example with model parameters $a_1 = 3.82, a_2 = 2.12, a_3 = 0.71, a_4 = 81.82$, and $a_5 = 24.06$,

$$A \ = \begin{bmatrix} a_1 + a_2 cos\bar{q}_2 + l_1{}^2(m_1+m_2); & a_3 + 0.5 a_2 cos\bar{q}_2 \\ a_3 + 0.5 l_2 cos\bar{q}_2 & a_3 \end{bmatrix} \tag{16}$$

$$B \ = \begin{bmatrix} -a_2 \bar{\dot{q}}_2 sin\bar{q}_2; & -a_2(\bar{\dot{q}}_1 + \bar{\dot{q}}_2) sin\bar{q}_2 \\ a_2 \bar{\dot{q}}_2 sin\bar{q}_2 & 0 \end{bmatrix} \tag{17}$$

$$C \ = \begin{bmatrix} -a_4 sin\bar{q}_1 - a_5 sin(\bar{q}_1+\bar{q}_2); & -a_5 sin(\bar{q}_1+\bar{q}_2) - a_2(\bar{\dot{q}}_1 \bar{\dot{q}}_2 + 0.5\bar{\dot{q}}_2^2) cos\bar{q}_2 \\ -a_5 sin(\bar{q}_1+\bar{q}_2) & -a_5 sin(\bar{q}_1+\bar{q}_2) + 0.5 a_2 cos\bar{q}_2 \end{bmatrix} \tag{18}$$

Taking the Laplace transform of Eq. 15 for the 2×2 robotic arm and noting that $\tau = MV$ and $q = CV$, the result is the following equation.

$$MV \ = (As^2 + Bs + C)CV \tag{19}$$

or

$$\begin{bmatrix} MV_1 \\ MV_2 \end{bmatrix} = \left\{ \begin{bmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{bmatrix} s^2 + \begin{bmatrix} B_{11} & B_{12} \\ B_{21} & B_{22} \end{bmatrix} s + \begin{bmatrix} C_{11} & C_{12} \\ C_{21} & C_{22} \end{bmatrix} \right\} \begin{bmatrix} CV_1 \\ CV_2 \end{bmatrix} \tag{20}$$

Eq. 19 reduces to Eq. 7 if $G(s)$ is taken to be equal to $(As^2 + Bs + C)^{-1}$, therefore $Q(s) = (As^2 + Bs + C)$. Applying the derivations for the feedforward controller of the 2×2 MIMO system leads to the following QFD matrix that utilizes the AD and DSM sections to fully describe the V-canonical structure in Fig. 7.

MV \ CV	CV_1	CV_2
MV_1	$G_{11} = \frac{1}{A_{11}s^2 + B_{11}s + C_{11}}$	$G_{12} = A_{12}s^2 + B_{12}s + C_{12}$
MV_2	$G_{21} = A_{21}s^2 + B_{21}s + C_{21}$	$G_{22} = \frac{1}{A_{22}s^2 + B_{22}s + C_{22}}$

CV \ CV	CV_1	CV_2
CV_1	**1**	$-\frac{A_{12}s^2 + B_{12}s + C_{12}}{A_{11}s^2 + B_{11}s + C_{11}}$
CV_2	$-\frac{A_{21}s^2 + B_{21}s + C_{21}}{A_{22}s^2 + B_{22}s + C_{22}}$	**1**

Fig. 7. QFD matrix of the 2-DOF PUMA 560 robot

Using the information provided in the QFD table, the feedforward controller for each loop is obtained as follows:

$$Q_1(s) \;= (A_{11}s^2 + B_{11}s + C_{11})CV_{1ref} + (A_{12}s^2 + B_{12}s + C_{12})CV_{2ref} \quad (21)$$

$$Q_2(s) \;= (A_{22}s^2 + B_{22}s + C_{22})CV_{1ref} + (A_{21}s^2 + B_{21}s + C_{21})CV_{2ref} \quad (22)$$

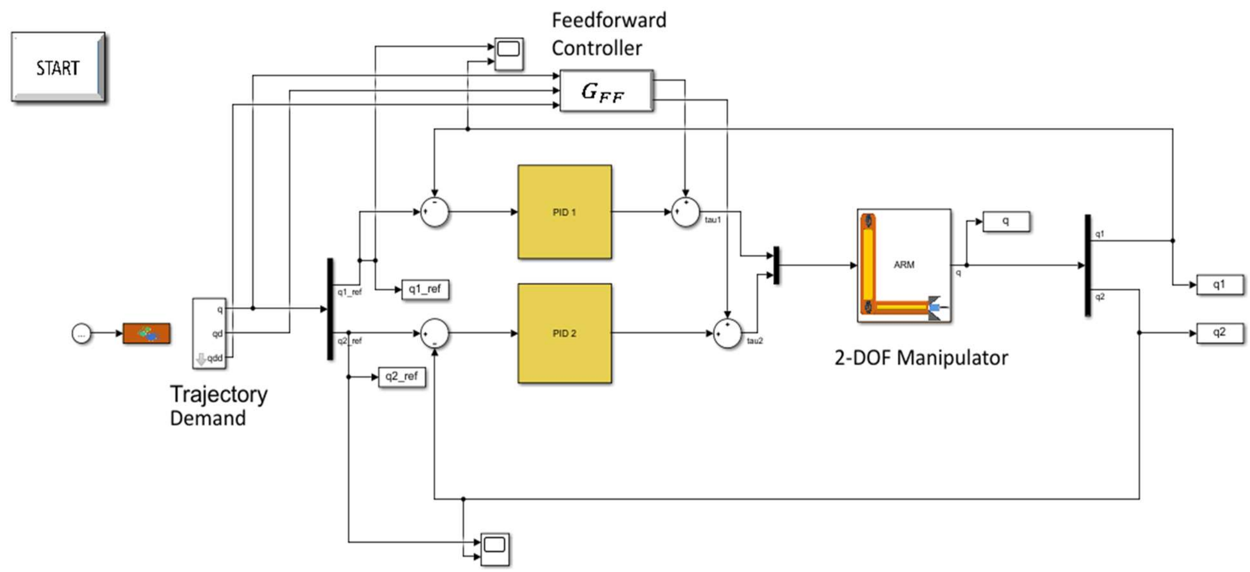

Fig. 8. Simulink control implementation of the 2-DOF robotic arm for an initial and final trajectory configuration of $\left[\bar{q}_1, \bar{\dot{q}}_1; \bar{q}_2, \bar{\dot{q}}_2\right]_i = \left[-\frac{\pi}{2}, 0; 0,0\right]$ and $\left[\bar{q}_1, \bar{\dot{q}}_1; \bar{q}_2, \bar{\dot{q}}_2\right]_f = \left[0,0; \frac{\pi}{2}, 0\right]$

Fig. 8 shows the Simulink model that implements the feedforward controller, G_{FF}, defined in Eqs. 13 and 14 and the PID controllers shown in Fig. 4 in controlling a nonlinear 2-DOF robotic arm. Fig. 9 shows the joint angular responses of the robotic arm to the trajectory configuration described in Fig. 6.

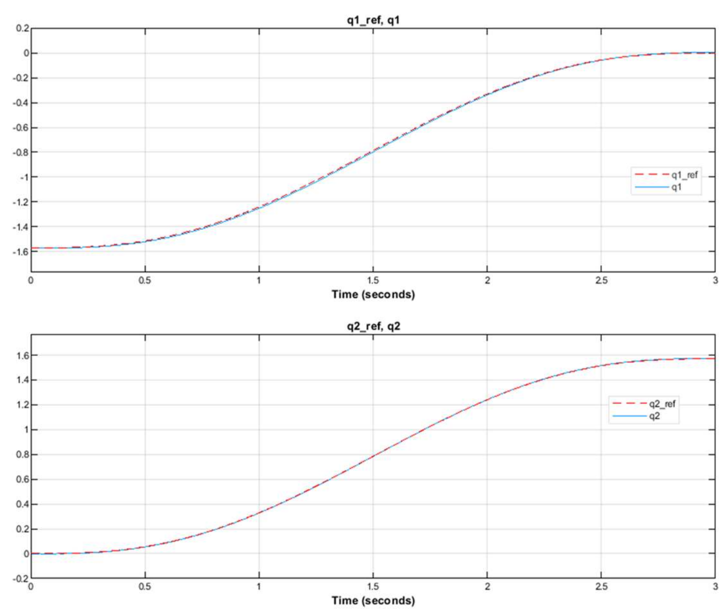

Fig. 9: Joint angle responses to the trajectory demand configuration of Fig. 6

4. Conclusion

A methodology for designing controllers at the conceptual design phase has been developed using QFD matrices. These control QFDs are extracted from the AD and DSM phases of integrated conceptual design. QFD, as a model-based approach to controller design, is a thought process that encourages creativity, collaboration, and communication as illustrated in the systematic representation and analysis of the dynamic structure of MIMO processes and their associated decoupling solutions in this paper.

When adopted in conceptual design, the matrix-based methodology provides a visual, compact, systematic, and transdisciplinary integrated MBSE approach [2]. It has been demonstrated that the structure of the control QFD matrix or matrices corresponds to a particular control strategy to adopt, signifying that the proposed methodology is indeed systematic. Although the emphasis on decoupling a QFD matrix limits the strategy to linear decoupling, the framework developed in this paper can be extended to incorporate nonlinear feedforward and adaptive linear feedforward strategies for future work.

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Cyber security challenges and vulnerability assessment in the construction industry

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Abstract

The construction industry is making a shift towards digitization and automation (known as Construction 4.0) due to the rapid growth of information and communication technologies as well as 3D printing, mechatronics, machine learning, big data, and the Internet of Things (IoT). These technologies will transform the design, planning, construction, operation and maintenance of the civil infrastructure systems, with a positive impact on the overall project time, cost, quality, and productivity. These new technologies will also make the industry more connected, and the consideration of cybersecurity of paramount importance. Although many studies have proposed frameworks and methodologies to develop such technologies, investigation of cybersecurity implications and related challenges have received very less attention. Some work has focused on security-minded BIM, but it lacks generality or does not consider an approach to determine the vulnerability of the different project participants, construction processes, and products involved during the different phases of construction projects. To address these limitations, this study a) develops a framework to identify cybersecurity risks in the construction industry, and b) assesses the vulnerability of traditional and hybrid delivery methods based on an agent based model (ABM). That is, the vulnerability of different project participants and construction entities during the different phases of the life-cycle of construction projects as a consequence of Construction 4.0. The findings from this study help to identify potential risks and provide a basis to assess the impact of interactions in a digital environment among different project participants. Future work aims to thoroughly investigate the proposed ABM approach and extend the same to other project delivery methods and information exchange networks in construction projects.

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Keywords : *Agent Based Modeling ; Construction 4.0; Cyber -Physical Systems ; Cybersecurity ; Smart Construction Sites ; Vulnerability Assessment*

1. Introduction

After a long history of under-digitization, the construction industry is making a shift towards digitization and automation due to rapidly growing information and communication technologies such as 3D printing, blockchain, and robotics. This is referred to as Construction 4.0, which is the construction industry's surrogate of Industry 4.0. The aim is to have connected systems at every stage in the life-cycle of a construction project, starting from the bidding phase to the end of life, including operation and maintenance. One of the key benefits of Construction 4.0 is the utilization of data as a result of digitization and connected systems during different life-cycle stages. Due to the nature of construction projects, large amounts of data are generated, such as competitive bidding information, design specifications, engineered calculations, intellectual property related information, pricing, profit/loss data, banking records, employee information, quality, safety, and productivity related standards and practices. In most cases, this data contains highly confidential, sensitive, or proprietary information.

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Industries operating in a digital environment become vulnerable to cyberattacks [1,2]. Some examples include data breaches that compromised credit card details of millions of customer, households, and small business at Facebook, Google, Home Depot, and JP Morgan [3-6]. Construction is no different when compared to other sectors such as banking, insurance, and health administration (e.g., hospitals). Moreover, the complex chain of interactions, dynamics, coordination, and data exchange between several inter-connected construction project participants pose unique performance, productivity, business, and security risks. Few of the reported cybersecurity instances include jeopardized security due to stolen floorplan files of the Australian intelligence headquarters in 2013 [7]. Economic risks were faced during the collection of deposits from applicants in the name of Komatsu, a well-known Japanese construction machinery manufacturer [8]. Konecranes lost about 17.2 million euros due to unwarranted payments [8]. A lot of construction employees' tax details and social security numbers of a US-based construction company, Turner, were compromised due to data sharing through unsecured channels posing business-related risks [8].

Therefore, stakeholders involved in the architectural, engineering, and construction (AEC) industry, and particularly construction companies, should be proactive by implementing strategies and educate employees in an effort to secure the data related to their projects. However, the reality is that awareness and investment in high-level security in the industry are still very low, making this industry susceptible and particularly attractive to hackers [8]. Therefore, a key element to be considered for the successful transition into digitalization of the AEC industry is the consideration of cybersecurity [9-11]. Furthermore, the challenges faced by construction are unique due to the complex interactions and objective of different participants. Identifying and assessing the cyber vulnerabilities of different construction parties/processes are fundamental and necessary before formalizing strategies to address them. The objective of this work is to a) develop a framework which academicians and construction professional can use to systematically identify cybersecurity risks, and b) assess the vulnerabilities concerning key construction participants (e.g., owner, designers and contractors), entities (e.g., equipment and assets), and processes (e.g., design intent discussion and sharing final models) using an agent based modelling approach.

2. Background

Before discussing the proposed framework, it is necessary to first understand the relevance of construction, security, cyber environment, and a few essential terms. The following three subsections discuss these aspects, starting with briefly defining terms, the relevance of cybersecurity, and vulnerability management.

2.1. Risk, threat, vulnerability, and outcome

Risk can be defined as the possibility of something bad happening [12]. Threat can be defined as an action or event which occur naturally or intentionally and has the potential to harm information, property, people, and the environment [13]. Vulnerability is the point of weakness or the state of being susceptible to an attack. It can be physical or psychological, such as a computing element (e.g., weak software program) or a behavioral trait (e.g., sharing sensitive files without encryption). This has the potential to make an enterprise, person, project, or equipment susceptible to an attack [13]. The result of an attack is the outcome. To summarize, threat, vulnerability, and outcome are sequential, with risk being a prelude to threat in most of the cases. That is, the existence of a threat indicates something bad can happen. Vulnerability assists the threat to do the harm. The outcome or the impact of this action is the harm done.

2.2. Cybersecurity

Cybersecurity can be defined as tools, policies, and practices to protect the data (stored and transmitted) and assets such as computers, infrastructure, and personnel [14]. The exposure to cyberattacks in the construction industry is amplified by the number of stakeholder and the long supply chains, mostly consisting of small businesses with limited resources devoted to information technology (IT). While most general contractors and large subcontractors can afford cyber-security policies, many smaller subcontractors cannot due to the limited profit margins. The risks of cyberattack also extend to different project phases. For example, during the planning and design phases, an attack on the BIM could compromise key project information, including personal data. It could also prevent access to the model or corrupt the project information, which might lead to performance and productivity risks in subsequent project phases (e.g., construction, operation and maintenance). In addition, as construction sites become more connected, digital platforms allow different project participants to access project data at the same time from different locations (currently using the combination of BIM and common data environments) with the ultimate goal to promote transparency and improve communication. Hence, it is evident that construction is not just a collection of different participants and equipment, but with the adoption of new technologies and digitalization of the sector, it is becoming a highly interconnected group of stakeholders during the whole life-cycle of a construction project. Thus, it is necessary to identify threats starting from the conceptual phase until the end of life (i.e., demolition). This could then be integrated into the existing risk management practices to devise better strategies, and improve the safety and security of the construction companies, professionals, products and services.

2.3. Assessing and managing risks

A general risk management process consists of three main elements: a) identification, b) assessment, and c) management [15]. Several different standards and studies have explored methods to asses and manage risks specifically focusing on the built environment security, and Building Information Modeling (BIM) data sharing. For example, the National Institute of Standards and Technology (NIST) developed a cybersecurity framework for assessing the management of critical infrastructure [16]. Others include the General Data Protection Regulation (GDPR) and Publicly Available Specification (PAS) 1192-5 [17-19]. In addition, some of the vulnerability assessment methods developed and investigated for other industries include probabilistic methods, attack graphs, Pareto diagrams, and process control charts [15, 20, 21]. Although these studies are helpful and relevant, they do not directly correspond to the construction phase due to the unique communication structure and corresponding cybersecurity challenges.

Some of the limitations of existing methods and standards can be summarized as follows: they a) mostly focus on building systems and data exchange security in the built environment, b) neglect bidding, planning, design, and construction phases, and c) do not investigate potential risks and impacts during the operation and maintenance phase by activities/actions performed during early stages of construction. One key contribution of this paper is mapping data flow as suggested by the NIST Framework (functional subcategory 3 of Identify-Asset Management), which is necessary to identify vulnerable systems and enable assessment of their overall risk.

3. Risk identification framework

The overall objective of the proposed framework is to identify avenues in which construction-related data could be directly or indirectly manipulated. These avenues can be directly related to the vulnerabilities discussed in the background section of this paper. That is, identifying these avenues form a primary step to assessing the outcome (e.g., cost of a data breach) of these vulnerabilities, and subsequently devise action plans (e.g., the cost to improving the security of the systems) to address them. Initially, the framework structure is discussed in the context of interactions between stakeholders in a construction project and between connected construction sites. Then, information exchange channels are detailed from a project level to site level. An overview of the framework methodology is shown in Figure 1, and is discussed in detail in the following subsections.

3.1. Step 1: Identify key entities (nodes)

The framework is based on the generic flow of information and communication exchange channels based on the traditional project delivery method (DBB). Although the subsequent discussion and figures are detailed based on DBB, the procedure remains the same for other types of delivery methods, and hence the generality of the proposed framework. We have identified five important entities, three of which are the main construction participants (as discussed in the introduction section) and two others, namely equipment (forms a primary basis for the execution of work) and asset (e.g., the realized physical product). Equipment refers to all the machinery (e.g., excavators and dump trucks) that directly or indirectly assists in the construction of the facility. Asset refers to any and all of the realization of the components being built, assembled, installed (e.g., foundation, reinforced concrete slabs, brick walls, ductwork, and fire hydrants), as well as additional tools (e.g., hardware and software) used to capture digital information of any granularity on the actual construction site. These five entities are referred to as nodes.

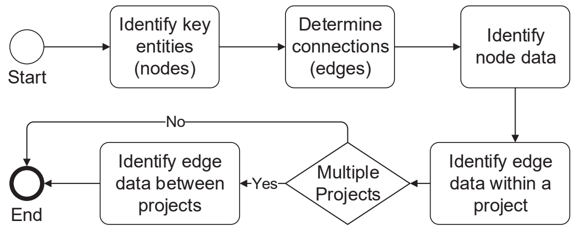

Figure 1. Step by step methodology of the proposed framework

3.2. Step 2: Determine connections (edges)

The connections (communications or information exchange channels) between the identified nodes are referred to as edges. Edges facilitate the exchange of information, communication, and coordination, which can directly or indirectly translate to digital information or data. Figure 2 shows these nodes and edges across different supply chain networks within the same project (shown vertically in Figure 2) or across different projects (shown horizontally in Figure 2). The idea is that the entire figure can represent subparts of a mega project or across different connected construction sites.

The objective of the following steps in the process is to describe the flow of data between the nodes (i.e., along the edges), at the nodes, and across the supply chain.

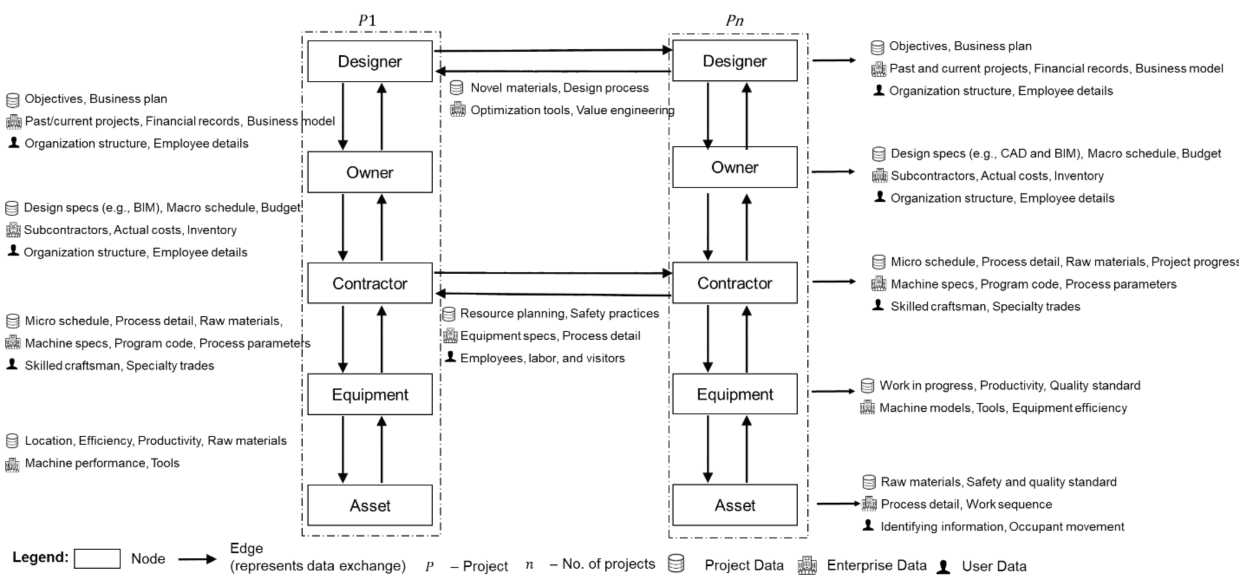

Figure 2. Information and communication exchange (edges) between key construction participants/entities (nodes) in a single project (vertical) across different projects (horizontal) for a traditional project delivery method along with some of the example data types at the respective nodes and edges

3.3. Step 3: Identify node data

The purpose of this step is to explore the different types of data that reside at each node. That is, the data that is stored at each of the significant construction entities identified in Step 1. Most of the data that flows between the nodes is stored at the nodes. However, only some data gets transferred through the edges. Thus, a generic classification of data that resides in the nodes can be static and dynamic data. Static data refers to the data that resides at these nodes, whereas dynamic data refers to the data that flows between nodes along the edges. This data is further classified into three subtypes based on the ownership of the data (e.g., project, enterprise, and user).

Project data refers to all the data related to the project, such as the design files, resources (i.e., materials and equipment), project participants, costs, and project schedules. Enterprise data relates to the data of companies directly or indirectly involved with the project (e.g., subcontractors and suppliers). Examples of such data include financial records of the company, actual labor or material costs, and other confidential or proprietary information. User data refers to the people, occupants, and visitors who are directly or indirectly associated with the project. Examples of data elements include demographic information, personal banking records, payroll and taxes, health insurance information, and other personal information.

Some of the usual static data that reside at their respective designer, owner, and contractor nodes include the cost to the company, bids, arbitrator details, and contingency plans. Some of the examples of static data at the equipment node level include equipment specifications, process parameters, work sequence, work efficiency, productivity, work in progress, and equipment model. Finally, asset node level data represent all the asset related data that can be physically or digitally accessed (e.g., due to sensors that belong to or are an integral part of the asset) such as raw materials, work in progress, tooling, and process sequence. In most of the cases, this static data is critical due to the involvement of sensitive information related to Intellectual Property (IP), trade secrets, business strategy, and market drivers. The above-discussed information is depicted in Figure 2. Steps 4 and 5 discuss the dynamic data and the data that flows between the nodes.

3.4. Step 4: Identify edge data within a project

With regards to the general information flow in construction, as shown in Figure 2, the initial interactions between the owner and designer (e.g., architect) usually correspond to the selection process of the designer. That is, data related to designer competitiveness and ability to handle the project such as the company portfolio, organization structure (e.g., key personnel), reputation, employees' technical expertise, and past projects. After the selection of the designer, the data typically includes understanding the objectives, goals, identifying and refining the business model, challenges, geographical, political, and cultural limitations, targets, and detailed design. At this point, a similar process to the one previously discussed is done for the selection of a general contractor or specialty subcontractors. All the data elements that were discussed above also flow along with that. After finalizing, the owner disseminates the respective pieces of information (i.e., sent by the designers) to the respective trades. Some the examples of the data types that flows along the owner-contractor edge are digital models, design specifications, master or detailed project schedules, design details, project goals and objectives, targets, budgets and cost estimates, inventory, etc.

At this level, the contractor and/or the subcontractors pass on this information to their personnel and subsequently to the equipment used to execute the tasks. Depending on the type of tasks performed, there can be different kinds of equipment used, such as equipment that is used to build things, some that assists during the process, some that monitors, and some that inspects. That is, digital models and process details required to construct a given component are fed to the equipment that builds that component. For example, a 3D printer used to build a concrete column is fed with the parametric model (i.e., geometry) as well as information about the raw materials involved, mix design, and water/cement ratio. The equipment that assists will get information such as raw materials, geometry, and site layout depending on the type of task. For example, an automated dump truck that takes out the excavated earth material from a construction site receives information regarding the site layout, soil characteristics of the site. Finally, the kind of data that flows between the equipment and the asset significantly constitute the sensory feedback information that guides the equipment to operate and perform tasks efficiently. These sensors belong to the asset due to functional or efficiency requirements, and are installed before or during the construction phase. For example, some sensors like cameras are installed on the site to help an excavator localize and autonomously perform tasks in construction sites [22]. Some examples of the type of data that flows include machine pose, real-time location of equipment, equipment and labor productivity, efficiency, and raw materials.

3.5. Step 5: Identify edge data between projects

For cases where more than one project exists (e.g., contractors or owners with a portfolio of projects), Figure 2 shows the schematic of data that flows between different projects. This can be envisioned in two ways: a) data that flows between different designer sub trades and subcontractors within a mega project, and b) data that flows between different connected construction sites in the same geographical region or with similar project goals. The objective is to improve safety and productivity by learning from each other's best practices. Although it is also possible that the owners of the respective projects communicate among each other, the type of data exchange remains significantly the same as between the contractors and designers. Hence, for the sake of simplicity of representation, only the data flow possibility between different sites among contractors and designers is represented and discussed. The flow of data between different designers of different projects includes the use of innovative materials, efficient products, better design process, and local code practices. Similarly, contractors can benefit significantly from each other pre, during, and post construction to improve site safety, maximize productivity, optimize costs, minimize wastes, and reduce emissions. The Construction Industry Institute (CII) based in the United States works closely with different construction companies on various projects across the globe to identify best practices across different trades in construction [23].

4. Vulnerability Assessment

The immediate step after identifying cybersecurity risks is to assess those risks. Vulnerability assessment can be defined as the process of assessing these risks, understanding the sources of vulnerabilities, and ultimately prioritize them before implementing technological solutions [24]. Several methods are suggested in the literature to assess the vulnerability of different systems and networks. However, for this study, an agent based modeling approach is chosen for analysis [25, 26] due to their ability to capture the complex interactions among various agents (e.g., construction participants) during the life cycle of the construction project [26]. The objective of this section is to develop an agent based approach and investigate two different construction network based on design-bid-build (DBB) and the Integrated Project Delivery (IPD) [27, 28, 29] (Figure 3). The reason for using these systems is to capture the variations of the contractual and communication relationships, and information exchange from different delivery systems.

4.1. Overview of the agent based model

The overarching objective of the agent based model (ABM) is to simulate the interactions of different construction participants. The ABM was developed in Python. Before proceeding to the explanation of the procedure, it is important to understand different states of the construction participants involved. The state here refers to the level of secureness of the individual or the entity (referred to as entities for the rest of the discussion) as suggested by Qu et al., [30]. Three states namely Normal (N), Uncertain (U), and Vulnerable (V) are considered. As the names imply, normal state refers to the entities being secure, uncertain refers to the entities not being very secure and prone to being vulnerable, and vulnerable means the security of the system is weak, and it can be easily compromised (or hacked). When participants interact with each other, the security of the information shared depends significantly on the security of the entities sharing that information. That is why, when two participants interact, it is highly likely that their states will affect each other. For example, a participant with a vulnerable state interacting with a participant with a normal state can impact and compromise the data of the participant with the normal state. An overview of the ABM used is described below.

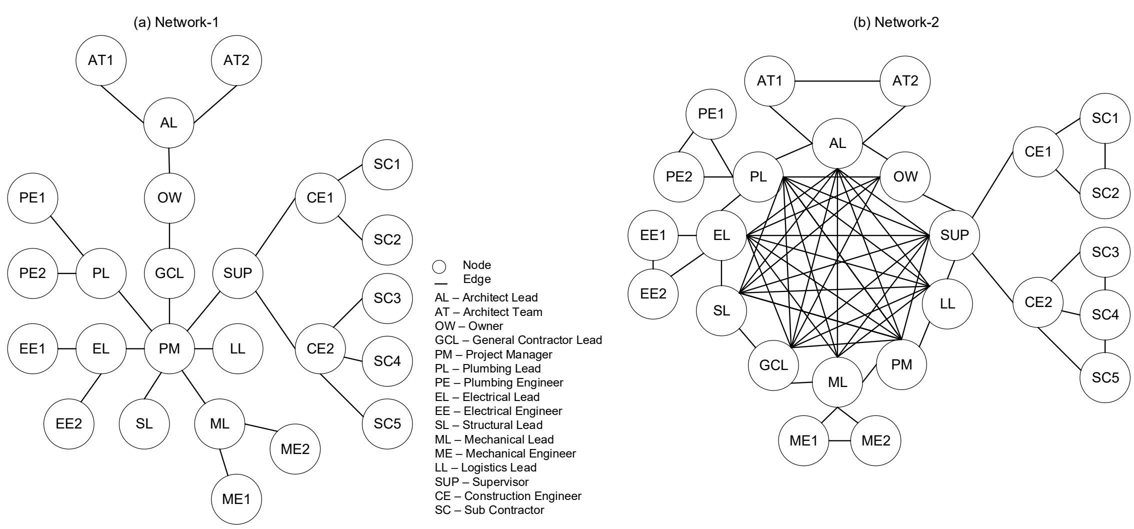

Figure 3. Construction interaction/information exchange (as represented by nodes and edges) networks based on the design-bid-build (Network-1) (a) and integrated project delivery (Network-2) (b) systems

Initially, all the construction entities (i.e., agents in the model) and the corresponding communication links (edges) involved are identified and represented in the form of a network. One of the three state characterization (N, U or V) is assigned to each entity and used as the initial system state. Then, interactions between entities are simulated for a possible change in their state. That is, first, each edge is randomly chosen among the available set of edges. The chosen edge represents the interaction between the respective nodes. The result of the interaction is either change in the security state of one of the entities if influenced (True) or no change at all (False). The state change depends on the level of interaction (LI), which varies between 0 and 1. The higher the LI, the higher the probability of a change of state. That is, if LI = 0, no state change will occur, and if LI =1, state change will happen. This can also be related to as the uniform (for LI = 0.5) or non-uniform (otherwise) random sample selection between True and False. For example, if LI = 0.25, there is a 25% probability that any of the interaction will result in a state change (i.e., True). As a proof of concept, in this study, a homogeneous selection of LI is considered where LI is a fixed value across all edges of the network. In addition, it is assumed that the conversion of states only occurs in the descending order of security. That is, the change only occurs from N to U to V state. For example, an agent with a normal state (N) converts into an agent with uncertain state (U) if the agent interacts with an agent with uncertain (U)/vulnerable (V) state. Similarly, an agent with an uncertain state (U) converts into an agent with a vulnerable state (V) if the agent interacts with an agent with a vulnerable state (V). These interactions are modeled for a specific number of iterations after which the algorithm is terminated. The final state of the entities is noted down for further analysis and comparison. For better understanding and easier replication, the Python implementation of the ABM developed for this study can be found in [31].

4.2. Scenario analysis, results, and discussion

For comparison reasons, two different construction networks (Figure 3) have been chosen due to their significant difference in the complexity of their interactions. Network-1 (Figure 3a) and Network-2 (Figure 3b), represent the DBB and IPD project delivery methods. The nodes represent the entities, and the edges represent the communication exchange channels. The simulation parameters and the results of the ABM are tabulated (Table 1). To better understand how the interactions influence the vulnerability of the network, all the participants are considered to be in a normal state (N), except subcontractor number 5 (SC5), which is considered a vulnerable agent. This represents the Base Case scenario shown in Table 1. The overall vulnerability of the two networks for the Base Case is very low (i.e., they are very secure) before the start of the simulation. The LI is considered to be 0.25 (i.e., there is a 25% probability of changing the state), which implies a conservative or low level of interaction. For each network, two different cases were simulated (a total of four cases). Without loss of generality, the algorithm is looped for 100 (Cases 1 and 3) and 300 (Cases 2 and 4) iterations. Since there is a probability associated with the selection of interaction and state change (i.e., LI), and to encapsulate a general trend in the results, each process is repeated a number of times; five in this study (i.e., Trials, as shown in Table 1). For purposes of this study, an agent (i.e., node) is considered a critical node when it is impacted (changed from N to U or V) two or more times during the five replications performed (#changes in Table 1). Though in this study entities signify construction participants, other entities such as systems, equipment, and assets in the construction site can be considered with such an approach. Furthermore, the algorithm developed [31] can be extended to conduct sensitivity analysis, compare, and analyze the security state results with varying values of LI.

The terminology related to the connections used to discuss the results is described below. First-layered connections are the ones that are directly connected to each other. For example, in Network-1, for node SC5, CE2 is a direct connection. Since SUP, SC3, and SC4 are directly connected to CE2, these nodes are second-layered connections to SC5. Similarly, PM is a third-layered connection to SC5. Results from the analysis of Case 1 show that the security state of three of the nodes such as SUP, CE2, and SC3 was impacted two or more times (2, 4, and 2 respectively in #changes in Table 1). It can thus be inferred that the vulnerability usually impacts the first-layered connections with a few exceptions to the second layer (e.g., SC3). Hence, the overall network vulnerability is not very critical since the security state of very few nodes became uncertain, and none of them became vulnerable. Surprisingly, a similar run on Network-2 (Case 3) did not have any effect on the other agents. That is, almost none of the nodes became uncertain or vulnerable due to the interactions. This is possibly due to the increase in the number of edges in Case 3 (i.e., 67 as compared to 24 in Case 1), and the reason why the interactions did not even impact the vulnerability of the first-layered connections. Therefore, it is reasonable to assume that with 100 iterations, the overall project security and performance will not be significantly impacted.

Case 2 and Case 4 were further investigated using 300 iterations. This is a proportional increase in comparison to the number of edges between Network-1 (24 edges) and Network-2 (67 edges), which is approximately threefold. As expected, the increase in the number of iterations in both cases (2 and 4) also increased the level of vulnerability (i.e., it was more apparent than in the previous cases (1 and 3)). For example, the vulnerability of Network-1 impacted the third-layered connections (e.g., CE1) in Case 2, as opposed to only the first-layered connections in Case 1. Similarly, the vulnerability of Network-2 impacted the third and fourth-layered connections in Case 4 as opposed to almost no impacts in Case 3. Comparing Cases 2 and 4, it can also be said that Network-2 is more impacted (i.e., vulnerable) than Network-1 for the same number of iterations. This is evident from the total number of critical nodes (8) in Case 2 when compared to the total number of critical nodes (14) in Case 4. More specifically, in Case 4, the vulnerability reached to the third-layered connections (e.g., OW and SL) and, in a few instances, affected fourth-layered connections (e.g., AT2).

Table 1. Agent based model results for both the networks DBB (1) and IPD (2) considered

Scenario	LI	#Iterations	Network	#Edges	Trials	OW	AL	AT1	AT2	GCL	PM	LL	SL	ML	ME1	ME2	PL	PE1	PE2	EL	EE1	EE2	SUP	CE1	CE2	SC1	SC2	SC3	SC4	SC5
Base Case	NA	NA	NA	NA	NA	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	V
Case 1	0.25	100	1	24	1	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	U	U	U	N	N	U	N	V
					2	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	V
					3	N	N	N	N	N	U	U	U	N	N	N	N	N	N	N	N	N	U	N	U	N	N	N	N	V
					4	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	U	N	N	N	N	V
					5	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	U	N	N	U	U	V
					#changes	0	0	0	0	0	1	1	1	0	0	0	0	0	0	0	0	0	**2**	1	**4**	0	0	**2**	1	-
Case 2	0.25	300	1	24	1	N	N	N	N	U	U	U	N	U	N	N	N	N	N	N	N	N	U	U	U	U	N	N	N	V
					2	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	V
					3	N	N	N	N	N	U	N	U	U	N	N	U	N	U	U	N	N	U	U	U	N	N	U	U	V
					4	N	N	N	N	N	U	N	N	N	N	N	N	N	N	N	N	N	V	U	V	U	U	U	N	V
					5	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	U	U	V	N	U	U	N	V
					#changes	0	0	0	0	1	**3**	1	1	**2**	0	0	1	0	1	1	0	0	**4**	**4**	**4**	**2**	**2**	**3**	1	-
Case 3	0.25	100	2	67	1	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	V
					2	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	V
					3	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	U	V
					4	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	V
					5	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	V
					#changes	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	-
Case 4	0.25	300	2	67	1	U	N	N	N	N	N	N	U	U	N	N	U	N	N	U	N	N	U	N	U	N	N	U	U	V
					2	N	U	N	N	U	U	N	N	N	N	N	N	N	N	U	N	N	U	N	U	N	N	U	U	V
					3	U	U	N	N	U	U	U	U	U	N	N	U	U	N	U	N	N	V	N	V	N	N	N	U	V
					4	N	U	N	U	N	U	U	U	U	N	N	U	N	N	U	U	N	U	N	V	N	N	V	V	V
					5	U	U	U	U	U	U	U	U	U	U	U	U	N	N	U	N	U	U	N	U	N	N	U	U	V
					#changes	**3**	**4**	1	**2**	**3**	**4**	**3**	**4**	**4**	1	1	**4**	1	0	**5**	1	1	**5**	0	**5**	0	0	**4**	**5**	-

From this study, the results suggest that IPD approaches (Network-2) are more vulnerable when compared to the traditional approach (Network-1). This is even valid for the most secure of the agent configurations, as considered as 'base case' in this analysis. Thus, it is of utmost importance to consider cybersecurity with high priority because even the slightest of the vulnerabilities among the entities might be harmful to the most secure entities. For example, as seen in the results, due to a vulnerable sub-contractor, the data at the owner node can be compromised. Also, it has to be noted that, in reality, there will be far more interactions than the number of interactions considered (up to 300 in this study). Hence, it can be reasonably assumed that the simulation results have the potential to closely represent actual scenarios. However, additional exploration and investigated into these models, which comprehensively consider all the project entities, is required to better understand the dynamics of the overall interactions among project participants, and closely represent ground truth observations.

5. Conclusion

Several cyberattacks have already occurred in the AEC industry with an intention to steal proprietary information, gain access to unauthorized files, and tamper existing records. As construction sites become more connected and digital platforms become the norm, cyberattacks will increase. Construction professionals need to be able to identify cybersecurity risks before assessing and formalizing plans to address them. None of the existing standards formulate a procedure to identify these risks, especially in construction. This paper proposes a generic framework to identify cybersecurity risks in construction. The methodology is based on the main entities (nodes) and the information and communication channels (edges) that exist in the construction industry. For the ease of classification, the data elements are categorized into three types (project, enterprise, and user data). The developed framework addresses one of the main outcomes of the NIST cybersecurity framework. In addition, an agent based modeling approach is developed for a preliminary understanding of the vulnerability assessment in construction. Scenario analysis was conducted using two construction networks based on DBB (design bid build) and IPD (integrated project delivery) methods. Results suggest that, even in the most secure agent configurations (only one agent being vulnerable), IPD networks are very susceptible to being compromised when compared to DBB. The model can also be used to investigate the cyber sensitivity of any construction network and to possibly identify critical communication links (edges), which are responsible for impacting the whole network. This might help to prioritize different risks and strategies based on respective outcome costs (e.g., the cost of increasing the cybersecurity of existing systems). Further investigation is required to integrate the cybersecurity risk identification into the existing risk management processes. As part of future work, the authors are expanding this model to comprehensively evaluate the vulnerability of different project participants, processes, equipment, and products for different project delivery systems, and different project phases (i.e., considering the entire lifecycle).

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Deep Learning-based Vehicle Image Matching for Flooding Damage Estimation

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Abstract

Images representing flooding damages can provide valuable information, such as the damage location and severity. Automated and quantifiable analyses of those images allow asset managers to accurately understand the vulnerability of the infrastructure. To this end, this paper proposes a methodology to match a vehicle in a flooding image to a 3D vehicle image. The proposed method is a part of a framework for flooding depth estimation. As the initial step of the framework, the proposed method uses Mask R-CNN and VGG network to extract the vehicle object and its features, respectively. The features of the vehicle images are compared with those of 3D vehicle image, to find a good match. A total of 87 vehicle objects were used to validate the proposed method, and promising levels of matching accuracy were obtained. Once the framework is completed, the proposed method is expected to automatically analyze flooding images for its damage assessment.

Keywords: Flooding damage; Vehicle image; 3D vehicle image; Image processing; Deep learning;

1. Introduction

Floods are one of the most dangerous and frequent natural disasters in the urban area, and have a great impact on road transportation. Road flooding due to heavy rain causes traffic accidents, traffic jam, and vehicle isolation. These disaster situations are often recorded by various types of cameras. CCTV (closed circuit television) cameras installed on the road or smart phone cameras carried by individuals can acquire photographs showing realistic disaster situations, and these images provide valuable information about the disaster. The ultimate objective of this study is to derive flooding damage information based on the image analysis of the vehicle, assuming that the vehicle is exposed to such a disaster situation. As a preliminary step to obtain the flood damage information, this paper proposes a method to match a vehicle in a flooding image to a 3D vehicle image. Once the matching is done accurately, the depth of the flooding would be able to be estimated.

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2. Methodology

Figure 1 shows the proposed method with a focus on the matching of vehicle images. Photos of flooded roads are processed to segment only the vehicle objects, which are later compared with 3D vehicle images. In the method, two deep Convolutional Neural Networks (CNNs) are used. The first CNN is Mask R-CNN [1] for the vehicle image extraction. The second CNN is the VGG network [2] for the feature extraction. The similarity comparison is finally conducted to find the best matching between the two cross-domain images.

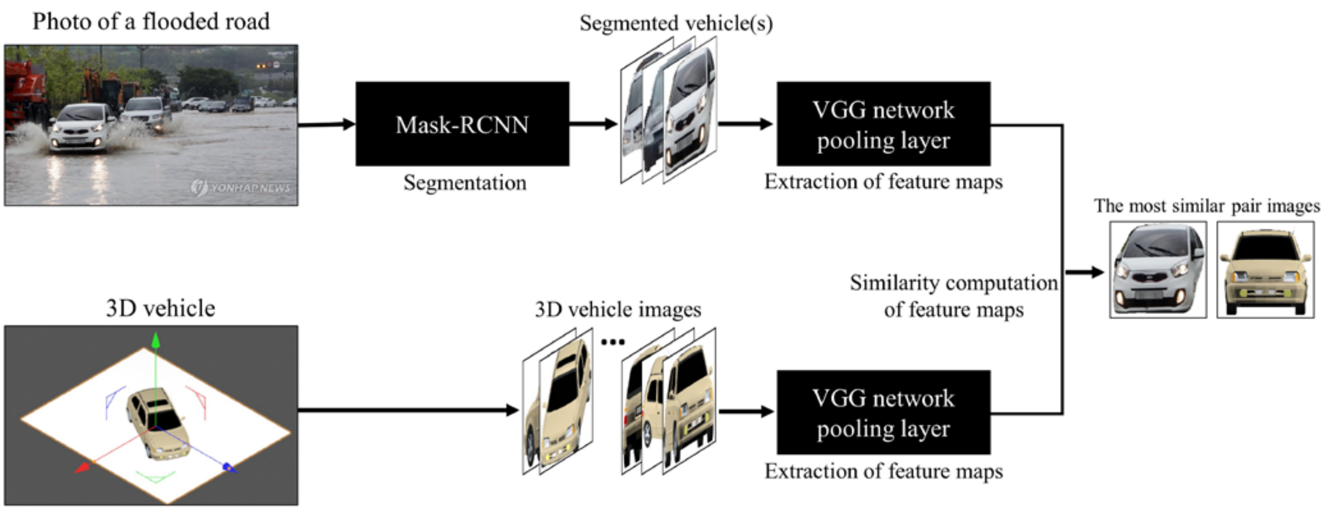

Fig. 1. The proposed method for matching a vehicle image and a 3D vehicle image.

2.1. Segmentation

Mask R-CNN is a deep learning model for object instance segmentation. Mask R-CNN extends Faster R-CNN [3] by including a mask branch for predicting segmentation masks [1]. Mask R-CNN were evaluated to be superior to previous approaches in the area of instance segmentation [1]. This paper, thus, used the Mask-RCNN pre-trained with the 80k images of COCO dataset [4].

2.2. Similarity comparison

Studies have been suggested to perform image retrieval using CNNs [5,6,7,8]. This paper used the method suggested by [8] for cross-domain image retrieval, in which the feature maps produced by the VGG network were vectorized and the vectorized feature maps were compared using the cosine distance. Feature maps are the output from a layer of a CNN and the input to the next layer of the CNN. Following the suggestions of [8], this study, for the comparison purpose, used the 4th pooling layer of VGG16 and VGG19 [2].

3. Experimental results

3.1. Data preparation

The images of flooded vehicles were obtained from photographs of the floods of Korea in July and August 2018. In this way, 25 article photos containing vehicles were selected. The input of pre-trained Mask-RCNN was the article photos, and the output was the segmented vehicles. The number of vehicle objects obtained from the 25 photographs was 274. Except for those vehicles whose size was very small or overshadowed by other objects, 87 were used as data for the similarity evaluation. Figure 2 shows examples of excluded vehicle data. 3D vehicle images were obtained by rotating a 3D vehicle model by 10 degrees in two viewpoints (parallel and from slightly above). As a result, 72 vehicle images were created. Since the input size of VGG16 and VGG19 was fixed to 224 x 224, all image data used for similarity calculation were resized to that size.

Fig. 2. Examples of excluded vehicle image.

3.2. Evaluation standards

As aforementioned, the 3D vehicle model was rotated by 10 degrees to acquire the data for image matching. Since a 3D model rotated by 10 degrees has similar visual characteristics to the image before rotation, the authors concluded that a difference in 10 degrees is negligible in the estimation of flood damage. Thus, the ground truth included a perfectly matched 3D image and a difference in rotation angle of 10 degrees to the left and right.

3.3. Results

Figure 3 shows examples of the matching results of the VGG16. As aforementioned, the fourth pooling layer of the VGG16 was used and the accuracy was 0.7356. The VGG 19 showed a slightly worse performance with an accuracy of 0.6092.

Fig. 3. Examples of the matching results of the VGG16.

4. Discussion and conclusions

In this study, 87 segmented vehicles from 25 article photos and 72 3D vehicle images were used as matching data. The 4th pooling layer of the VGG16 achieved better results than the 4th pooling layer of VGG19, with an accuracy of 73.56% and 60.92%, respectively. As show in Fig. 4, segmented cars were in some cases represented as broken images because they were immersed in water or covered by other objects. However, even those broken images were able to be matched with 3d-images. This is because the feature maps of the 4th pooling layer of VGG extract structural characteristics rather than detailed characteristics [8].

This paper proposed a deep learning-based method to match between a vehicle in a flooding image and a 3D vehicle image. The proposed method was a part of a framework to automatically analyze images containing flooding situation. Mask R-CNN and VGG network were the major components of the proposed method, for vehicle extraction and feature extraction, respectively. The level of matching accuracy was promising for achieving the ultimate objective of the framework–the flooding depth estimation.

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Development Priorities and Key Challenges of Automation and Robotics in High-Rise Building Construction

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Abstract

The construction industry is facing the challenges of low productivity, poor working environment, safety problems, an aging workforce. Particularly in high-rise building construction, these problems are serious because of the larger labor demand and a more dangerous working environment. Automation and robotics are expected to provide solutions to these problems while the level of application in the construction industry is still very low. This study identified development priorities (DPs) and key challenges (KCs) of automation and robotics in high-rise building construction through a questionnaire survey and an international expert workshop. Based on literature review and brainstorming, preliminary needs and influential factors were identified and a questionnaire was designed. The questionnaire survey was then conducted among senior engineers from major construction companies in China, evaluating the needs and influential factors related to robotics implementation. Based the results of the survey, an international workshop was held to furtherly identify DPs and KCs. This paper presents the processes and results of both the questionnaire survey and the workshop, identified and analyzed the DPs and KCs, and makes suggestions for future approaches to applying automation and robotics in high-rise building construction.

Keywords: automation and robotics; development priority; high-rise building construction; key challenge

1. Introduction

Low productivity, poor working environment and safety problems are still enduring concerns at construction sites. Also, as the problem of aging becomes more and more serious, the labor costs of on-site construction are growing rapidly. The increasing number of the world's high-rise buildings exacerbates these problems because it requires a larger quantity of labor force and working in high elevation leads to safety risks. As conventional construction methods have reached their limits to meet the growing need of the construction industry [1], automation and robotics are expected to replace on-site human labor and improve productivity and quality. A number of studies on construction automation and robotics emerged since the 1980s, developing various types of systems and technologies with successful practical applications in construction projects or even commercial products. Based on the results of these studies, researchers made efforts to encourage the adoption and implementation based on ergonomic and economic analysis, application decision-making frameworks and identification of barriers [2-5]. However, the application of

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automation and robotics at the construction sites remains limited and the right approach to promote it in mid-21st century is still unclear.

Therefore, this paper aims to focus on high-rise building construction and seek answers to the above problem by investigating development priorities (DPs) and key challenges (KCs) with a questionnaire survey and an international expert workshop. It is believed that the results would be helpful for both academia and industry to decide on the future development of automation and robotics in high-rise building construction. The remainder of this paper is organized as follows. In Section 2, the research method is introduced. Section 3 presents the questionnaire survey as well as the preparation based on literature review and brainstorming, and Section 4 describes the process and analyses the results of the workshop. Section 5 summarizes the findings and proposes suggestions for future research and application.

2. Method

In terms of construction automation and robotics, three main parties are directly involved, i.e., researchers, robot or other automated equipment developers (hereinafter referred to as robot developers), and construction companies. Generally, researchers conduct basic research on knowledge and technologies; robot developers produce robots based on the research results; construction companies make use of the robots for practical application. Duties of the three parties are sometimes partially overlapping. For example, some robot developers conduct research independently and some construction companies can develop robots or automation equipment by themselves.

Therefore, the identification of DPs and KCs of automation and robotics in high-rise building construction requires participation and joint efforts of all three parties. With regard to DPs, both the market needs and the technical feasibilities should be considered. The needs could be distinguished by construction engineers with rich on-site experience, while the technical feasibilities could be judged by researchers and robot developers. As for identification of KCs, face-to-face discussion is needed because each party has its challenges, affected by multiple influential factors.

According to the above analysis, a mixed research method was used in this study, as shown in Fig. 1. This method includes a questionnaire survey towards construction companies to get a general picture of the needs and influential factors from the perspective of construction practices, and an international expert workshop for discussions among all parties. Since it is hard for construction engineers to come up with their own ideas on needs and influential factors in a questionnaire survey, we prepared preliminary lists of needs and influential factors based on literature review and brainstorming, and requested the engineers to evaluate their significances.

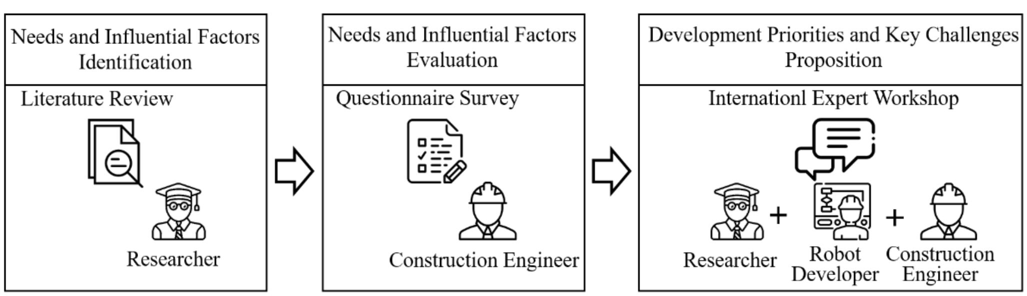

Fig. 1. Overview of research method.

3. Needs and influential factors of applying automation and robotics in high-rise building construction

3.1. Preliminary identification based on literature review and brainstorming

The preliminary identification of needs and influential factors was carried out by literature review and brainstorming. According to Standard of Construction Classification (GB/T 50840-2013), a national construction standard in China, building construction work can be classified into several categories, including earth and foundation, superstructure, decoration, etc. Considering the features of high-rise buildings and referring to existing reviews on construction automation and robotics [6-9], we brainstormed possible needs in each category. For influential factors, the themes of reviewed studies are not only limited to construction automation and robotics but also include the application of other information technologies, such as BIM, because they are considered to have common traits and tend to be influenced by similar factors. Table 1 and Table 2 respectively show the identified needs and influential factors. The columns of mean and rank present the results of the following questionnaire survey, which are illustrated in Section 4.

Table 1. Preliminary needs & evaluation results of the questionnaire survey

Needs	Mean	Rank	Needs	Mean	Rank
1. Earth moving	3.26	18	*11. External wall painting	3.67	9
2. Horizontal site logistics of materials and equipment	3.54	12	12. Floor tiling	3.53	14
*3. Vertical site logistics of materials and equipment	3.85	5	13. Concrete finishing	3.54	13
*4. Steel welding	4.36	1	14. Ceiling installation	3.25	19
*5. Steel assembly	3.67	9	15. Partition wall installation	3.29	17
*6. Steel coating	3.98	3	16. Door and window installation	3.15	20
*7. Monitoring of the deformation and internal force of the steel structure	4.29	2	17. Material quality inspection	3.52	15
*8. Prefabricated component assembly	3.81	6	*18. Construction quality inspection	3.78	7
9. Curtain wall installation	3.65	11	*19. Monitoring of construction equipment	3.74	8
10. Façade tile installation	3.45	16	*20. Protection of work performed overhead	3.89	4

Table 2. Preliminary influential factors & evaluation results of the questionnaire survey

Influential factor	References	Mean	Rank	Influential factor	References	Mean	Rank
*1. Labor cost of construction	[1,10]	3.82	9	12. Policy on environmental impacts of construction	[15]	3.61	20
*2. Initial investment cost of automation and robotics technology	[5,11]	4.41	1	13. Globalization in construction (new technologies, foreign labor, etc.)	[16]	3.30	21
*3. Uncertainty of the economic benefit of automation and robotics	[10-12]	3.94	4	*14. Governmental support on academic research of construction automation and robotics	[11,15,16]	3.87	7
*4. Maturity and proven technology to provide robust performance and ease of use	[1,5]	4.19	2	*15. Governmental support on automation and robotics application in construction	[11,16]	3.91	6
5. Mature skill training to acquire new technologies	[12,13]	3.65	19	16. Culture of innovation	[5,16]	3.78	12
6. Adaption to the traditional construction method	[1,12]	3.71	16	17. Public awareness of environmental protection	[12,15]	3.80	11
7. Attention to new technologies in the industry	[14]	3.73	13	*18. Social attention to occupational safety & health	[10,11]	3.86	8
8. Research and development capability of construction companies		3.70	17	*19. Age structure and education of the workforce	[1,11]	3.82	9
*9. Application of other information technologies (BIM, IoT, etc.)	[14,15]	3.95	3	20. The scale of prefabrication	[17]	3.72	14
10. Labor policy	[15,16]	3.71	15	*21. The ability of on-site management	[11,12]	3.94	4
11. Government policy on time limit for the projects		3.69	18				

3.2. Evaluation based on a questionnaire survey

An online questionnaire was adopted, which included four sections. The first section is a brief introductory letter presented the research objectives and the author's contact details. The second section solicited the profiles of the respondents and their organizations. In the third and fourth sections, the preliminary needs and influencing factors identified above were listed respectively. The respondents were requested to rate the level of significance of the needs and influencing factors with five-point Likert scales (rate from 1-5, 1 for very insignificant, and 5 for very significant).

On selection of potential respondents, we focused on senior engineers from recognized construction companies, because these companies tend to have adequate resources for implementation of automation and robotics. We sent the link of the questionnaire through emails and messages to those in the expert databases of China Construction Industry Association (CCIA) and China Civil Engineering Society (CCES), which include experts from the most recognized construction companies in China. Survey responses were collected in three months, from June to August 2018. During this period, 795 questionnaires were sent out, and 108 valid ones were obtained, with a response rate of 13.6%.

Table 3 shows the profiles of the respondents and their companies. The distribution of respondents' positions and work experience indicated that they have high expertise in construction and their opinions would have significant effects on the future development of their companies. The responding companies covered different scales (small 14.8%, medium 42.6%, and large 42.6%) and were distributed in different areas throughout the country (East China 37.0%, North China 26.9%, South China 15.7%, Central China 7.4%, NorthEast China 5.6%, NorthWest China 3.7%, and SouthWest China 3.7%). According to the qualification standard for construction companies in China, most responding companies had super grades or first grades of qualifications in general contractor (92.6%), steel structure works (69.4%), decoration works (67.6%), earth and foundation work (63.0%), etc., which suggested their high professional construction abilities. Among the responding companies, 94.4% had experience of applying BIM, and a considerable amount of them had applied IoT, big data, AI, and automation and robotics, which indicated their positive attitude of embracing new technologies in construction. Thus, the responding companies are considered to represent the key potential users of construction automation and robotics in China. It is noticed that although 90.7% of respondents agreed with the necessity of applying automation and robotics in high-rise building construction, only 18.5% of their companies had specific plans in their future projects.

The evaluation results of the needs and influential factors are shown in Table 1 and Table 2. The overall mean scores of the needs range from 3.15 to 4.36, and those of the influential factors range from 3.30 to 4.41. The top 10 needs and top 10 influential factors were marked with asterisks (*).

Table 3. Profiles of respondents and their companies.

Respondents	N	%	Responding Companies	N	%
Position			**Company scale (number of employees)**		
Chief engineer/deputy chief engineer	53	49.1	Small (<600 employees)	16	14.8
General manager/deputy general manager	12	11.1	Medium (600-3000 employees)	46	42.6
Technical director	31	28.7	Large (>3000 employees)	46	42.6
Others	12	11.1			
Work experience			**Have experience of applying the following technologies**		
< 5 years	6	5.6	Building Information Modeling (BIM)	102	94.4
5-10 years	14	13.0	Internet of things (IoT)	43	39.8
11-15 years	7	6.5	Big data	34	31.5
16-20 years	11	10.2	Artificial intelligence (AI)	26	24.1
21-25 years	23	21.3	Automation and robotics	26	24.1
> 25 years	47	43.5			
Agree with the necessity of applying automation & robotics in high-rise building construction	98	90.7	**Have specific plans for applying automation & robotics in future projects**	20	18.5

4. Development priorities (DPs) and key challenges (KCs)

To identify DPs and KCs, an international expert workshop was held in November 2018. Thirteen top experts of relevant fields in the world or in China were invited to participate in the workshop, including seven university professors (two from China, two from US, one from Germany, one from Japan, and one from Canada), and six industrial practitioners (three senior engineers from construction companies in China, two specialists from a construction automation software company in China, and one vice president from a robot developer in China).

In order to ensure smooth communication and discussion, the experts were divided into two groups according to their languages, including an English group (five experts) and a Chinese group (eight experts). In each group, each expert listed top three DPs and top three KCs of automation and robotics in high-rise building construction in the first 30 min, referring but not limited to the lists of top 10 needs and top 10 influential factors received from the questionnaire survey. In the next 60 min, each expert shared ideas about his lists, and other experts discussed the ideas. Finally, the experts spent another 60 min for further discussion and formed a list of top three DPs and a list of top three KCs. The results are listed in Table 4.

Table 4. Top three DPs and top three KCs proposed by two groups

Rank	DPs (English group)	DPs (Chinese group)	KCs (English group)	KCs (Chinese group)
1	Protection of work performed overhead	Prefabricated component assembly	Uncertainty of economic benefit	Immaturity of technology
2	Monitoring of construction equipment	Facade construction and maintenance	Immaturity of technology	Lack of data and analysis on user demand
3	Steel works (coating, welding, etc.)	Construction quality inspection	Incompatibility of existing construction pattern and robot application	Incompatibility of existing construction pattern and robot application

The two groups presented six different ideas of DPs in total. In the English group, the top two DPs are both safety issues, respectively focusing on overhead construction work and construction equipment, because robots are expected to conduct safety monitoring and protection jobs for both workers and equipment. Steel works, such as steel coating and welding, received the third position in the English group. Although a large proportion of steel works happen in factories where robots are widely used, others still need to be conducted on site, especially some difficult works for complex joints or components. Researchers and robot developers still have a long way to go from the viewpoint of improving the industrial robots for on-site steel works. In the Chinese group, 'prefabricated component assembly' was ranked top. This echoed the policy of prefabricated building action plan, i.e., improving the proportion of prefabricated building in new building area in China to 15% by 2020, which is part of China's 13th Five-Year Plan. Since prefabricated components are more standard, it would be easier for the robots to handle them. The second DP in the Chinese group was 'façade construction and maintenance', which has been a popular research topic of high-rise buildings for over 30 years with various products, and future work is expected to provide more flexible and safe solutions. The third one was 'construction quality inspection'， which would be a suitable job for robots because they are efficient in dealing with numerical indicators and always honest with the data. Considering the large volume of quality inspection work, robotics can not only save labor but also reduce the work volume with the selection of appropriate statistical and sampling methods. Besides, robots are capable of inspecting narrow or dangerous locations onsite which are difficult for workers to reach.

As for KCs, the two groups presented four in total, including two same ones and two different ones. The top KC in the English group was 'uncertainty of economic benefit', which is a typical problem appearing in most cases of promoting new technologies. Immaturity of technology received both the second position in the English group and the top position in the Chinese group. Researchers have achieved remarkable successes in construction automation and robotics, but only a few of them are mature enough to be translated into practical use. For the two KCs above, more demo tests should be conducted before application, and small-scale and easy applications would be more acceptable. The third KC in both the English group and the Chinese group was 'incompatibility of existing construction pattern and robot application', which concerned that the need of applying automation and robotics are not taken into account in the existing designing processes, construction methods and construction organization. To cope with this challenge, the construction phase needs to be re-designed and integrated with the design phase, so that new robots could be developed under a standard framework of integrated design and construction. Another KC in Chinese group was 'lack of data and analysis on user demand', receiving the second position, which indicated that some of existing robotic technologies and products are not exactly fit in with the user demand. A possible reason for this problem is the information access-related isolation of different parties. Therefore, all parties need to develop more communication and cooperation so that the researchers and robot developers could grasp the true demands of the construction industry.

5. Conclusion

Consistent application of automation and robotics are expected to improve the construction industry in many aspects. Although many efforts have been made in this field over the last three decades, the application rate at the construction sites is still limited. Therefore, this study focused on high-rise buildings, conducted a questionnaire survey and an international expert workshop, investigated and analyzed DPs and KCs, and proposed resulting suggestions. The top DPs include protection of overhead construction work, monitoring of construction equipment, steels works, prefabricated component assembly, façade construction and maintenance, and construction quality inspection. The top KCs include immaturity of technology, incompatibility of existing construction pattern and robot application, uncertainty of economic benefit, and lack of data and analysis on user demand. These findings are expected to be valuable for researchers, robot developers and construction companies to further develop and refine appropriate concepts and apply automation and robotics in high-rise building construction.

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Exploiting automated technologies for reduction of rework in construction housing supply chain

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Abstract

Housing has been experiencing significant rework within the supply chain. Rework has afflicted both cost and schedule of projects due to the complex environment, intricate activities and highly fragmented nature of housing supply chain. Housing supply chain generate immense data and share information with different parties, which contribute to multitude of countless challenges. As a result of rework, productivity and workflow of information in construction supply chain has been affected with a catalogue of problems for the past few decades. Automation in construction supply chain with novel technological and analytical strategies has aspired industry to improve the productivity and change the trajectory of traditional, manual and analogue way of processing. The aim of this study is to explore possible opportunities of employing new technologies and challenges involved in utilising automated technologies for minimising rework in housing supply chain. The research methodology is based on a review of literature to investigate automated technologies to eliminate rework in housing supply chain. A conceptual framework is proposed to determine the suitability of various technologies to fully automate housing supply chain and facilitate the reduction of rework in construction housing supply chain.

Keywords: Automated technologies; housing supply chain; offsite manufacturing; robots; AI; reduction of rework

1. Introduction

Construction housing supply chain is characterised by highly fragmented data, and has often been criticised for low productivity and poor practices and inability to deliver high-quality products [26,44,51]. The workflow of process and the adaptation of innovation have always been elusive and/or obsolete [20,44]. The quality of information and the precise interpretation significantly affects both costs and scheduling throughout housing supply chain. Yet, interaction among different players at key stages of construction process with a broad spectrum of information is poorly co-ordinated and not readily shared due to the complex nature of housing supply chain. Reports by both Egan [14] and Latham [35] indicated that, the fragmented construction supply chain has been affecting the level of productivity and performance and there is a need for innovation to improve the overall performance of construction building industry.

Rework is a chronic issue in housing supply chain, and has an adverse impact on the level of productivity of building in the UK [5,17,25,26,40,42,43]. However, despite the considerable plethora of research on construction industry [37, 40], there is a very limited evidence of research on the barriers of minimising rework in housing chain, particularly in the light of recent technologies advancement [7,17,26,28,45,53,63]. Reduction of rework among the subcontractors in housing supply chain, plays a crucial role in the quality, time and cost of the production process. In housing supply chain, there is scope for the sources of rework to be controlled and managed through automation to avoid repetitive

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mistakes and errors caused by humans. Given the context, the sources and impact of rework has always been an issue for key players and contributors in the housing supply chain. The aim of this study is to identify possible opportunities on how automation in housing supply chain can lead to elimination of rework. Potential approaches for minimisation of rework will be reviewed by exploring various technologies to facilitate automation of housing production processes. The study involves a two-stage process to develop a strategic framework for minimisation of rework in housing supply chain. The first stage of the literature review focus on various technologies such as artificial intelligence, off-site technologies used for industrialised housing, robotics, and, digital twin to address the problems of rework within housing supply chain. The second stage involves the development of a conceptual framework based on the outcome of the literature review to determine the suitability of technologies that can be used to address the root causes of rework in the housing supply chain.

2. Literature Review

The following sections discuss the complexity of housing supply chain, causes of rework in housing supply chain and technologies that can be utilised to eliminate rework.

2.1 The unique characteristics of UK housing supply chain

The heterogeneous characteristic of housing supply is embedded with highly fragmented and intricate activities. Generally, the UK construction industry, and particularly housing supply chain has a plethora of privately-owned companies. As a consequence, high level of fragmentation is driven by a significant number of micro businesses in the UK housing supply chain [4]. Almost 70% to 90% of jobs in housing supply chain are subcontracted to small and specialised firms, where 99% of firms are Small Medium Enterprise (SMEs), with an employment ratio of 2 to 5 people [4]. However, there has been less attention paid to the importance role of the supply chain given the high level of fragmentation associated with large number of subcontractors. This particular feature has contributed to the significant level of fragmentation and rework occurrence in housing supply chain.

2.2 Causes of rework

Fragmentation has been considered as one of the main causes of rework generation within housing supply chain. [62,63]. Traditionally, the root cause of rework in housing supply chain has been identified as a poor management of main contractor [62]. A literature review suggests that managerial aspects are one of the crucial factors that is contributing to rework [29,38,39,43,45,53]. Project characteristics have also been identified as another factor affecting the performance of housing supply chain's coordination. These include; project duration, project costs, number of stories, building type and procurement methods [40]. One of the predominant factors that causes rework is human error which can occur due to lack of knowledge and mistakes [39,41,45]. However, many studies on rework have failed to precisely assess the impact of human's underperformance and how to address the issue [28,53,45]. Two prominent causes of rework during production process have been suggested as; information flow among contract control and client's unexpected changes [38][63]. The root causes of rework in construction housing supply chain from a review of literature [1,15,43,46,62] are summarised as follow: 1) Fragmentation and subcontracting; 2) Noncompliance with specification; 3) Unrealistic scheduling; 4) Untimely supply of materials; 5) Poor documentation; 6) Lack of clear instruction to workers; 7) Lack of skilled labour; and 8) Ineffective project management.

The exponential growth of technologies has created new avenues for automation in housing industry to optimise operation, minimises human errors and improves construction performance. Potential exists from utilising offsite manufacturing and partial application to fully robotically automated on-site fabrication process to eliminate rework and improve the productivity in construction industry [9].

2.3 Benefits of offsite manufacturing in housing

There are different terminologies used for industrialised construction in the literature, such as: off-site production (OSP) [39,49]; off-site manufacturing (OSM) [42]; prefab [57,58]; modern methods of construction (MMC) [54]

Fig. 1. The adaptation of industrialised housing hierarchy [19]

industrialised construction [36] and modular construction (Modular) [50]. A very simple hierarchical model was introduced to differentiate the level of industrialisation of construction works [19] as shown in Figure 1. Traditional construction is fully craft-based construction using workmanship in which all the processes happens at the site and involves *in situ* manufacturing and installation of prefabricated elements such as doors, windows, pipes, bricks, tiles, etc. On-site prefabrication is the assembly of building components *on-site which are then moved into position* (components such as timber framing, handmade roof trusses and façade units). As opposed to on-site prefabrication, the off-site prefabrication is *assembly of building components and then transporting them to site* and assembling in place such as air conditioning units or roof trusses. Pods are pre-assembled units such as such toilets or bathrooms manufactured off-site and then transported to site to connect them to other building elements. Complete modular encompasses fully finished units that form the complete structure and form a building [20]. However, manufactured modular housing has often been neglected, as construction industry has a tendency of being very slow to adopt and proceed with new advanced technologies.

Off-site technologies have enormous potential to reduce negative environmental impacts, increase re-use of recycling material [8,23,59], eliminating waste, minimising rework, reducing cost, and optimising the performance and the quality of construction projects [18,19,24,24]. There are countless advantages associated with manufactured housing over traditional construction method, such as higher precision, more energy efficient to operate and cost efficiency. This result in shortening the completion process of building with higher quality. One of the significant benefits of fully automated off-site manufacturing in construction projects is eliminating human errors (which results in rework generation) as well as preventing the adversity of site condition (i.e., weather, etc.) on the quality of the completed project. These aspects can significantly reduce rework and consequently prevent projects from cost and schedule overrun. It has been found that manufactured housing can save up to 20% of time compared to on-site construction in Hong Kong construction projects [27]. There are numerous indirect benefits associated with off-site prefabrication due to reduced site preliminary costs, reduced site congestion and earlier income generation for clients [19], [3]. [85]. In addition, it has been shown that off-site prefabrication can also reduce safety risks around 35% due to less site congestion and removing operatives from a dangerous site environment to a controlled factory environment with better working conditions [35, 23, 8].

A survey of the top 100 UK housing builders agreed that to attain high quality in utilising off-site prefabrication is the most crucial motivation [51]. Another study found that off-site prefabrication could reduce the need for many trades that are in short supply, thus, can eliminate necessary rework significantly within different supply chain [3]. However, capacity constraints in the supply chain, lack of technology awareness; cultural perception; lack of business process model; high initial investment costs; incompatibility and inflexibility of design are identified as the most challenging barriers for off-site manufacturing [7,19,21,37]. For instance, in Hong Kong the Provisional Construction Industry Coordination Board has noted that high initial investment remains a significant obstacle to the adaptation of off-site prefabrication techniques and to unleashing the full potential of cost savings [7,21]. [7][19][37] identified that the inflexibility of design was a major issue for off-site prefabrication due to the requirement of an early design freeze. The findings were supported [24,37] who argued that the main barriers of off-site prefabrication were cost, design incompatibility and flexibility issues. Logistics and transportation also have been seen as major impediments to the adaptation of off-site prefabrication [21,49].

2.4 The idea of Digital Twin

Digital Twin (DT) can help off-site prefabrication with inflexibility of design issues. A DT is a digital copy of a physical construction component in which by bridging the physical and the virtual world, data is transmitted seamlessly allowing the virtual copy to exist simultaneously with the physical component [68]. Construction is seen as a manufacturing process where DT can help to overcome the disadvantages of off-site manufacturing assembly, quality issues including design errors [65]. A fully robotically automated fabrication process in off-site manufacturing with the support of DT will enable digitised visualisation of a virtually replica of a physical subject in a factory floor to improve the quality issues and keep monitoring products' maintenance with installed chips. DT can help eliminate all modification needs, errors relating to design and human misprediction and detection. This will lead to a shorter lead-time, improve the quality of products, minimise rework and reduce costs in fully automated manufactured housing.

2.5 Robotics in construction

Housing supply chain consists of a defined set of sub-activities such as; handling, concreting, coating, measuring, and assembling in iterative stages. In construction sites, the degree of automation is relatively low, the final assembly of building components heavily rely on human. The most significant impact robotics systems have had on the housing construction has been on off-site fabrication, which involves using robots in a controlled environment. Housing characterised by highly fragmented tasks that has infinite opportunities for automation. The application of robotics is well advanced in manufacturing industry and continuously expanding into construction industry. The application of robotics in construction has been progressing well to reduce time and cost associated with operation, as robots have the potential to attain productivity in construction performance, and improve efficiency, safety, and quality [2]. Construction robots are classified into three types [55]: 1) teleoperated systems where robots are under human control 2) programmable construction machines, in which humans insert the specific programmed menu of function or provide the instruction of new function to robots, and 3) intelligent systems, in which fully autonomous robots accomplish required set of activities without human intervention. A plethora of research and development (R & D) in the utilisation of robotics in construction led to an extensive range of different application primarily on civil infrastructure and residential buildings, such as automation of road, concrete compaction, interior finishing and tunnel and bridge construction [2,10,22]. A few studies have been conducted to analyse productivity and cost of construction robots. It was noted that applying robotics for on-site surface finishing work, particularly for repetitive tasks can be plausible from the technical performance and economic perspective [11,60]. In a similar study, it was suggested that utilising robotics for straight forward and repetitive tasks in building construction is more economical than traditional methods [47]. Another study compared the level of productivity between robots to human in relations to time and cost, and demonstrated the significant improvement of productivity employing robots in building construction [64]. Other researchers [60],[66] examined the productivity improvement of concrete paving employing robotics for the operation, and the result was that the production rate improved 22% compare to traditional approaches [11,60].

2.6 Employing Artificial Intelligence for rework reduction

The prediction of rework in housing supply chain has always been determined using a trial and error process, which has a tendency of escalating the uncertainty of a project. Accurate prediction strategy for housing supply chain provides a remedy for the root causes of rework. The application of artificial intelligence (AI) in housing supply chain can improve the predictability of projects' outcome accurately, before construction take place [40,48]. This can address quality issues and detect human errors at the early stage of each task before proceeding into the next stage. AI can be used as a consultant to subcontractors in the housing supply chain for enhancing strategic decision making and to deploy the most optimised methods to eliminate rework and improve the quality of finished products in housing supply chain. AI can be also used to improve the performance of a fragmented housing supply chain embedded with a large number of subcontractors. However, there are obstacles to be considered. Understanding the real phenomena of AI and trust among subcontractors to deliver a project have been identified as a significant barrier over the past few decades in construction industry. Over the past few decades, number of prediction models including artificial neural networks (ANN) and Ant Colony Optimisation (ACO) have been developed for estimating and predicting construction wastes (including rework), based on regression analysis (RA), case-based reasoning (CBR), and support vector machine (SVM) [16,30,32,33,34]. However, there is limited evidence of research employing AI for elimination of rework in the housing supply chain.

3 Towards the development of a conceptual framework

Given the range of technological options and advances in automation, there is a need to determine the suitability of various technologies to fully automated housing supply chain and facilitate the reduction of rework. A conceptual framework is proposed initially to focus on the potential for automation in housing supply chain. The framework can identify technologies that are most suitable to address a particular problem or to optimise the performance of an activity, which can result in elimination of rework, and productivity improvement in housing supply chain (see table 1). For instance, one of the causes of rework in housing supply chain is human error [40,45], which can be addressed with support of robots. Another distinct example is unexpected design errors and changes as a consequence of unilateral client change [26,41,45]. This can be addressed with utilising offsite manufacturing to reduce errors and changes or employing AI to predict the possibility of error occurrence in early stage of design.

Table 1. The role of technologies to automate the characteristics of housing supply chain

	Requirement characteristics of housing supply chain	Offsite prefabrication	AI	Robotics	Digital Twin
Critical	Ability to rectify errors and mistakes	x	x	x	x
	Reduction of design errors and changes	x	x	x	x
	Effective communication		x	x	x
	Management of change	x	x	x	x
Core	Improvement of collaboration	x	x	x	
	Improvement of Transparency and trust		x		x
	Realistic scheduling	x	x		
	Reduction in reliance on skilled workforce	x	x	x	
	Effective document control and archiving		x	x	x

Co-ordination is extremely challenging due to the complex environment associated with production process. Some of the changes during the design and construction stages are inevitable due to errors, mistakes, untimely supply of material and unrealistic scheduling [61]. Automation has a capacity to address these issues as well as the catalogue of other challenges in the housing supply chain such as skills shortages, document control and archiving, collaboration, and defining appropriate construction methods to minimise the cost of changes, speed up the process, and improve productivity through digested platform can run for example with AI and robots. Automation can provide the most efficient way for an informed decision making to minimise the causes of rework.

Conclusion

Automated processes in the construction industry can improve the flow and accessibility of data. A fully automated process will facilitate the reduction of rework across different projects in housing supply chains. Technologies such as digital twin incorporated with off-site prefabrication can improve the quality of off-site manufacturing products in housing, reduce unintended errors and effectively monitor the maintenance of components over a period. Automation through visualisation model can help designers and engineers reduce the misinterpretation of data and improve collaboration and communication through digitised platform. Robots and AI can reduce design errors and changes and, improve the performance of projects, as demonstrated in other industries. Applying such technologies in housing supply chain can eliminate the unintended errors and mistakes and significantly reduce the occurrence of rework.

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Fuzzy Logic and Neural Networks for Insulation Fault Diagnosis in Construction Robots Drives

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Abstract

In building industry reliable uninterrupted power supply of construction robots drives is of particular importance, which is largely determined by reliable trouble-free operation of generating equipment. According to statistics, the majority of electricity in the world is produced by hydro and turbine generators, which are low-speed or high-speed synchronous machines. The urgent problem is the development of methods for non-destructive testing and insulation monitoring of synchronous machines. The main method of assessing the real technical condition is insulation control through the analysis of electrical discharge activity (EDA). This method allows detecting defects at an early stage of their development.
The actual problem is the development of automatic technical state diagnosis methods for insulation by the EDA parameter. The main parameters that are evaluated in the analysis of EDA is the shape and amplitude of the discharge phenomena.
The article proposes a method for determining the discharge phenomena form, based on a neural network classification model. It used two-layer network of direct signal transmission trained by Levenberg-Marquardt algorithm.
A method for determining the degree of defect development based on a neuro-fuzzy diagnostic model, differing by a joint analysis of the shape, amplitude and repetition rate of the pulses of a discharge phenomenon, which allow to determine the degree of defect development by relating it to one of the classes of diagnoses is proposed.

Peer-review under responsibility of the scientific committee of the Creative Construction Conference 2019.

Keywords: construction robots; electrical drives; diagnostics of isolation of a synchronous machines; electric discharge activity; fuzzy logic; neural networks

1. Introduction

At the present time, the age of most electric power converters in the world exceeds 30 years, so the actual question is how to optimize the costs of maintaining these devices in operation. The most vulnerable part of the generator is winding insulation. Earlier, diagnostics of winding isolation of generators were carried out according to [1-3], based on the results of "classical" tests by the increased voltage at idle. The given tests give the answer only to a question: "has sustained - has not sustained" and do not allow to find a residual resource of the equipment, therefore an actual problem is development of methods of not destroying control and insulation monitoring. For rotating machines, to which the generator belongs, the main method of assessing the actual technical condition is the insulation control. This method allows not only to detect defects, but also to classify them according to the degree of danger of the detected defects. The method is based on multiple control and recording at the operating voltage of the main characteristic parameters of insulation. By the obtained results judges as the degree of aging of the winding insulation,

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the degree of wedging and the state of the housing insulation, and the state of the magneto-drive [4]. The analysis [1-4] of methods of nondestructive insulation control showed that the method of electric discharge activity (EDA) allows the most complete identification of the main insulation defects of the generator. Measurement of EDA is carried out with the help of specialized equipment [3], and the analysis is performed manually by an expert.
In the process of analyzing EDAs, significant importance is given to the form of discharge phenomena [3]. Three main forms of discharge phenomena are known: partial discharges; spark discharges; arc phenomena. It is also possible and their combinations for slot discharge phenomena, breakdowns between the plates of the active steel package, discharges during the motion of mobile ferromagnetic particles. Examples of typical oscillograms of partial discharges are given in Table. 1.
In addition to the form of discharging phenomena that allow to detect insulation faults, an important characteristic in evaluating the EDA is the fixation of the distributions *n(Q)*, (*Q* is the amplitude of the pulse, and *n* is the number of pulses from the discharges during the time of the industrial frequency period) [3]. In addition to the number of pulses, the mean and maximum pulse amplitudes are estimated.
Discharging phenomena are quantitatively characterized by the apparent charges *Q* of single discharges and the frequency of their following *n*. For diagnostic troubleshooting, the pulse following frequency *n* is measured - with the voltage amplitudes *U*. As a result of measurements, the distribution of the number of pulses from partial discharges (PD) is formed per unit of time from the amplitude value, i.e. *n(Q)*. Measurement and analysis of the mean (Q_{av}) and maximum ($Q_{\max}$) values of the pulse amplitude, as well as the average number of pulses from the discharges (n_{av}) during the period of the industrial frequency let to reveal the main faults in the insulation of the generator and assess the current state of the object.
Based on the results of the EDA analysis, generators are divided into two groups:
- the first group - serviceable with a satisfactory condition of isolation;
- the second group - with unsatisfactory condition of isolation, which requires an extraordinary, i.e. more frequent periodic monitoring.
The first group corresponds to two types of diagnoses: "Norm", "Norm with deviation (ND)", to the second "Norm with significant deviations (NSD)" and "Worsened".
Thus, to determine the current state of the generator, it is necessary to establish the form of discharge affects, referring it to one of the classes (Table 1), and to determine the amplitude and frequency of the pulses and, according to Table 2, to establish the technical state of the generator, referring it to one of four classes: "Norm", "NWD", "NSD" or "Impaired". To automate the analysis of the EDA of a generator, it is advisable to use methods of artificial intelligence, namely a combination of apparatus of non-clear logic and neural networks.

2. Neural network model for determining the shape of phenomena discharges

In the process of diagnosing a generator in terms of EDA parameters, an important indicator is the form of discharge phenomena. According to [4], each characteristic failure detected by dint of EDA corresponds to a certain form of discharge phenomena [5], which allows unequivocally to determine the malfunction. The accumulated long-term experience has made it possible to compile a list of typical characteristic types of the signal of electric discharge activity [6].
At present, the task of recognizing the shape of discharge phenomena is done manually, which is very laborious and requires a lot of experience from an expert who performs diagnostics. For the automation of this process, a neural network for classification of a technical condition is proposed, having the structure shown in Fig. 1.

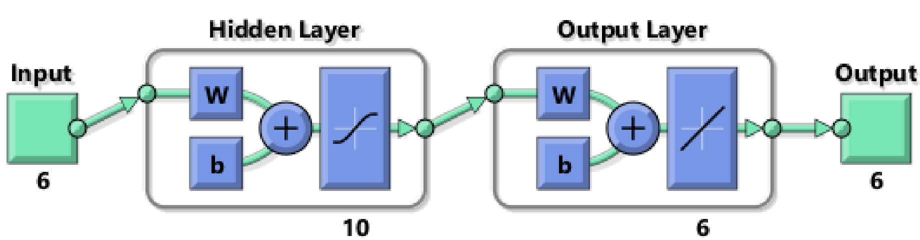

Fig.1. Neural network of the classification of the form of discharge phenomena

As the initial data, discharge phenomena typical for all known faults are used, as well as for serviceable objects whose oscillograms are currently estimated by the expert visually. The network egress is the conditionally given fault number: "0" a fault-free generator, "1" sparkage on the crowns of the teeth, "2" is discharges between the active steel plates, "3"

- slot discharge, "4" is partial discharges in the case insulation on the surface of the rod, "5" - the presence of mobile ferromagnetic particles.

To teach the neural network, the Levenberg-Marquardt algorithm [7] is used, which is designed to optimize the parameters of nonlinear regression models. The algorithm consists in successively approximating the given initial values of the parameters to the desired local optimum. The results of teaching the neural network are shown in Fig. 2.

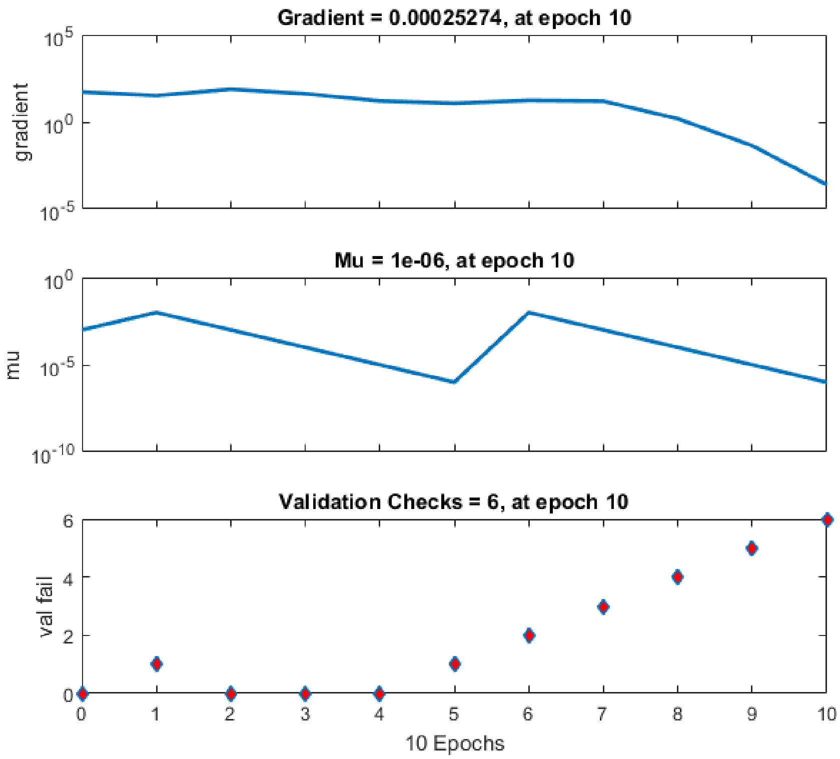

Fig.2.The result of teaching the neural network of classification of the form of discharge phenomena

As a result of the operation of the network, from each output will be obtained a vector-string of the length equal to the input vector containing the class number. For the convenience of analysis, it is necessary to find the mean value and round it according to the rules of mathematics. To test the teached network, samples of the teaching choice were alternately submitted to the input, and the network unmistakably assigned them to a given class. Next, a vector-string of discharge phenomena received from several different turbo-generators was fed to the input of the neural network, and the network accurately determined the type of signal.

After detecting the shape of the discharge phenomenon, it is necessary to determine the degree of development of the malfunction by analyzing the amplitude and frequency of the signal. EDA. From Table 1 is to see that to determine the degree of development of the five faults of the turbogenerator, it is necessary to evaluate $Q_{max,}Q_{\text{av}}$ and n_{av}. The set of values and the range of their change is different; hence, the use of the fuzzy logic apparatus will allow to separate the data of the fault and of the extent of their development with a sufficiently high accuracy.

To identify the stage of defect development, a neural-fuzzy model has been created whose inputs are: the number of the signal waveform obtained as a result of the classification by means of the neural network described in section 3.2 (Fig. 3a), the current values of the measured parameters $Q_{max,}Q_{cp}$ and n_{cp} Fig. 3 b, d), the outputs - the degree of defect development (Fig. 3, e).

For the entered fuzzy sets is formed the knowledge base according to Table 1 and 2. If, as a result of the analysis of the form of discharge phenomena, the value is set to "0", which corresponds to the absence of a defect, then the technical condition is "Normal". With an output value of "5" - the presence of mobile ferromagnetic particles is a "Weakened" state. For other faults, the rules are set according to Table 1.

To convert the well-defined values of input to well-defined values of output is used the n – input algorithm of fuzzy logical inference Mamdani [8]

Table 1 - Classification of the technical state of the generator as a function of the amplitude and number of pulses

Fault	Generator condition	Q_{av}, мВ	n_{av}, имп/пер	Q_{max}мВ
Sparks on crowns of teeth	NSD	more 100	more 15	
	Worsened	more 1000	more 30	
Discharges between of plates	NSD			more 5000
	Worsened			more 15000
Slot discharge	NSD			more 3000
	Worsened			more 8000
Partial discharges in the case insulation	ND	more 1500	more 2	
	NSD	more 3000	more 3	
	Worsened	more 5000	more 4	
Partial discharges on the surface of the rods	ND	more 2000	more 1,5	more 4000
	NSD	more 4000	more 4	more 8000
	Worsened	more 6000	more 4	more 10000

The graphical interpretation of the knowledge base is the response surface, an example of which is shown on Fig. 4.

The resulting fuzzy model allows us to divide the existing faults into a model of four classes of diagnoses: "1" - "Norm", "2" - " ND", "3" - " NSD", "4" - "Worsened". In the case of the appearance of a fractional number, it must be rounded according to the rules of mathematics.

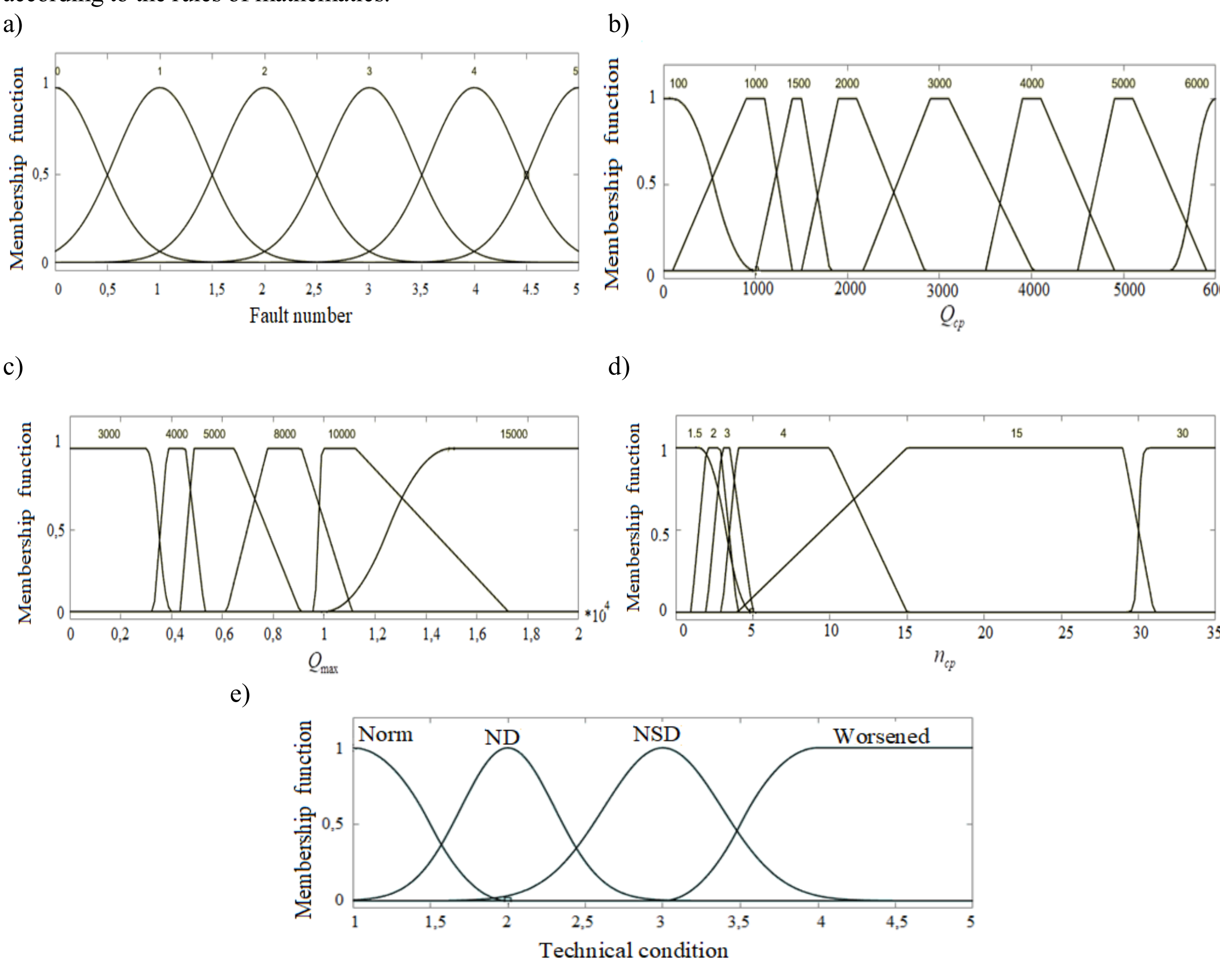

Fig.3. Inputs (a-d) and output (e) of a fuzzy model for estimating the degree of development of insulation defects by the parameter EDA (electric discharge activity)

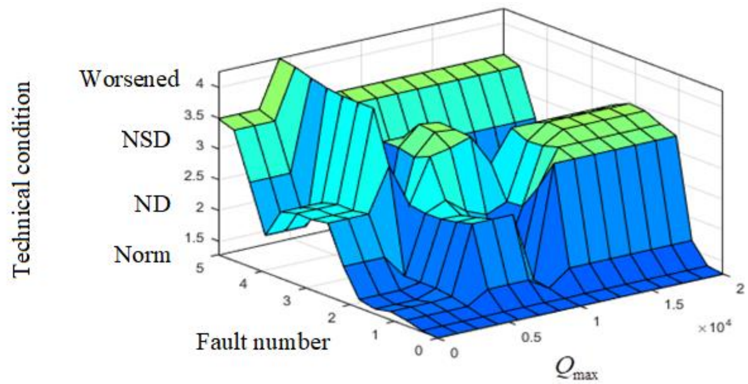

Fig.4. The response surface of the fuzzy model for determining the degree of defect development (the maximum pulse amplitude for various faults)

This fuzzy model allows to determine the amplitude and intensity of discharge phenomena at one control point, while the generator has impressive dimensions and a lot of control points located at different locations of the object and requiring measurement at different points. Therefore, in order to obtain a complete turbogenerator diagnosis model, it is necessary to unify the submodel data, according to the design of the object.

To determine the current technical state of the whole generator, it is necessary to use this model. If as a result of measuring the EDA at the control point several faults can be detected, then to determine the current technical state it is necessary, using the proposed model, to find the current state of the generator at each point, and then approximate the results of the models. Since the development of any failure leads to the failure of the whole object and the overall technical state of the turbogenerator is estimated at the worst of their states, then as the approximating function is chosen the function of maximum.

To solve the approximation problem, a radial basis network is modeled, the input layer of which implements the distribution of image data for a hidden layer of weights consisting of radial basic neurons using the Gaussian activation function whose mappings are fed to the output layer of linear neurons [8]. Sending the vector-column of the coefficients of the current development trend of the faults to the input of the radial basis network, and setting the target vector as the maximum function of input, the value of the diagnostic function will be obtained at the output of the radial basic network, which enables us to estimate the current state of the object, according to one of the known classes of diagnoses. The structure of this submodel is shown in Fig. 5.

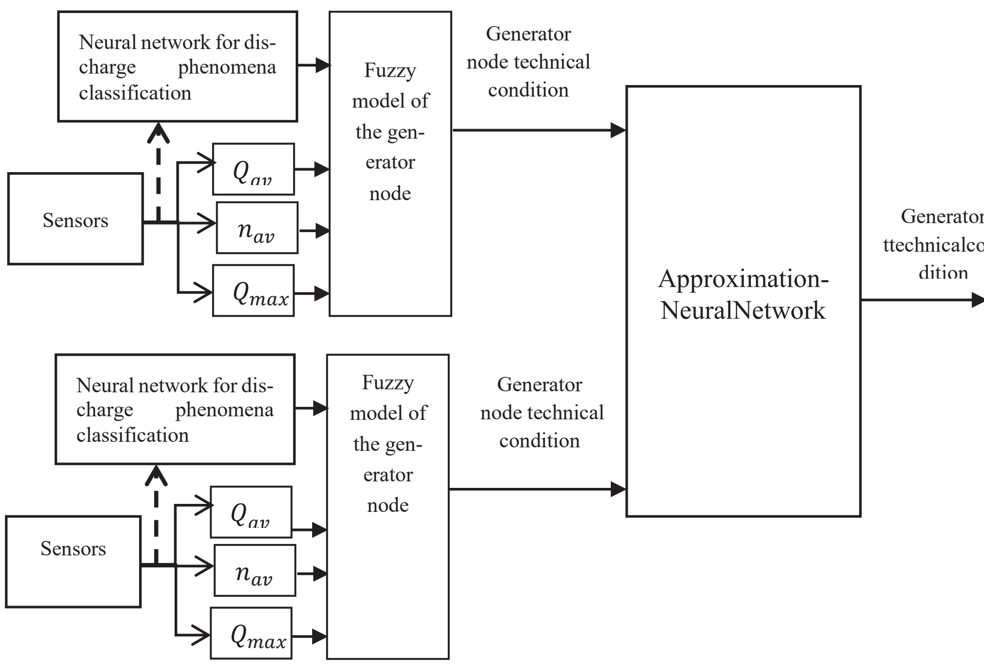

Fig. 5. Model of diagnosing insulation of a generator according to EDA parameters

The given model allows to determine the current technical state of the generator based on the shape, amplitude and frequency of the pulse of the ERA and to determine the degree of development of the fault by according it to one of the four classes: "Norm", "ND", "NSD", "Worsened".

Conclusions

It is established that the main reason for the failure of generators is the violation of insulation. One of the most accurate and accessible methods of monitoring the state of isolation is the analysis of EDAs, allowing by the form of the discharge phenomenon, the average and maximum value of the pulse amplitude and the number of pulses, to determine the current state of the object, referring it to one of the classes of diagnoses: "Norma", " Norm with deviation"," Norm with significant deviation", "Worsened" and find the reason for the refusal. Application of this model will significantly simplify the process of analyzing parameters, significantly reducing the time of diagnosis.

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Identification of the interlayer bond between repair overlay and concrete using nondestructive testing, an artificial neural network and principal component analysis

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Abstract

In construction practice, concrete elements are exposed to adverse environmental influences, and therefore sooner or later require repair. This repair is usually performed by removing the damaged concrete and replacing it with repair overlay. The quality of this repair is evaluated using the destructive pull-off method. In this method, the pull-off adhesion value between the repair overlay and repaired element is measured (f_b). Unfortunately, the disadvantage of this method is local damage of the element at every measuring point. It is therefore reasonable to present a reliable nondestructive method of identifying the interlayer pull-off adhesion value. The article presents the results of experimental research, which indicate that such identification is possible using complementary non-destructive methods and an artificial neural network with principal component analysis.

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Keywords: concrete interlayer bond, adhesion, nondestructive testing, artificial neural network, principal component analysis;

1. Introduction

Concrete structures and elements are exposed to adverse environmental and service influences, which sooner or later cause the destruction of the subsurface concrete. Depending on the type and time of these influences, the thickness of the damaged concrete may even be several dozen millimeters. Repair of the element is then required, which extends the time of its safe exploitation. The repair is very often performed using a special repair mortar, and the element after repair becomes de facto layered [1]. It is known from construction practice that the thickness of the damaged concrete is not usually the same over the entire surface of the element, and therefore the thickness of the repair overlay is not the same. Regardless of how thick this layer is, it is necessary after the repair to perform quality control of the bonding with the repaired element. The measurable value of this bonding is the value of pull-off adhesion f_b, determined in construction practice using the pull-off method.

The pull-off method is used to control the bonding between the repair overlay and the concrete substrate. Apart from the basic advantage of quantifying the value of the pull-off adhesion, it also has a significant disadvantage. This is local damage to the repair overlay that occurs in every measuring area, which then requires a costly and time-consuming repair after completion of the tests. In the case of large-area concrete elements, the number of control (measuring) areas is counted in hundreds, because according to [2], one measurement should be performed at every

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3 m^2. It is therefore reasonable to present a non-destructive method of evaluating the interlayer bond between the repair overlay and the repaired element, thereby significantly limiting the above-mentioned disadvantage.

Due to the fact that the pull-off adhesion value f_b is affected by the preparation of the repaired element surface [3, 4], it may be presumed that the parameters describing this surface morphology can be useful for the non-destructive identification of this bonding [5]. These parameters can be obtained, for example, by means of non-destructive testing using the three-dimensional laser scanning method that is carried out on the surface of the layer prepared for repair. In addition, other non-destructive methods may be useful in identifying the bonding between the layers in the repaired concrete elements. Using the acoustic methods [6], it is possible to obtain parameters on the surface of the repair overlay.

Taking the above into consideration, the aim of this paper is to show that the identification of the interlayer bond between a concrete repair overlay of variable thickness with a repaired element (substrate) can be performed using the above-mentioned complementary non-destructive methods and an artificial neural network with principal component analysis.

2. Description of performed tests

The research involved two double-layer model concrete elements marked with Roman numerals I and II, which are shown in Figure 1. They were used to build a research database consisting of parameters that describe the surface morphology of the concrete substrate representing the repaired element, the parameter describing the thickness of the repair overlay, the parameters assessed using acoustic methods on the surface of the repair overlay, and also the pull-off adhesion of the repair overlay and substrate obtained using the pull-off method.

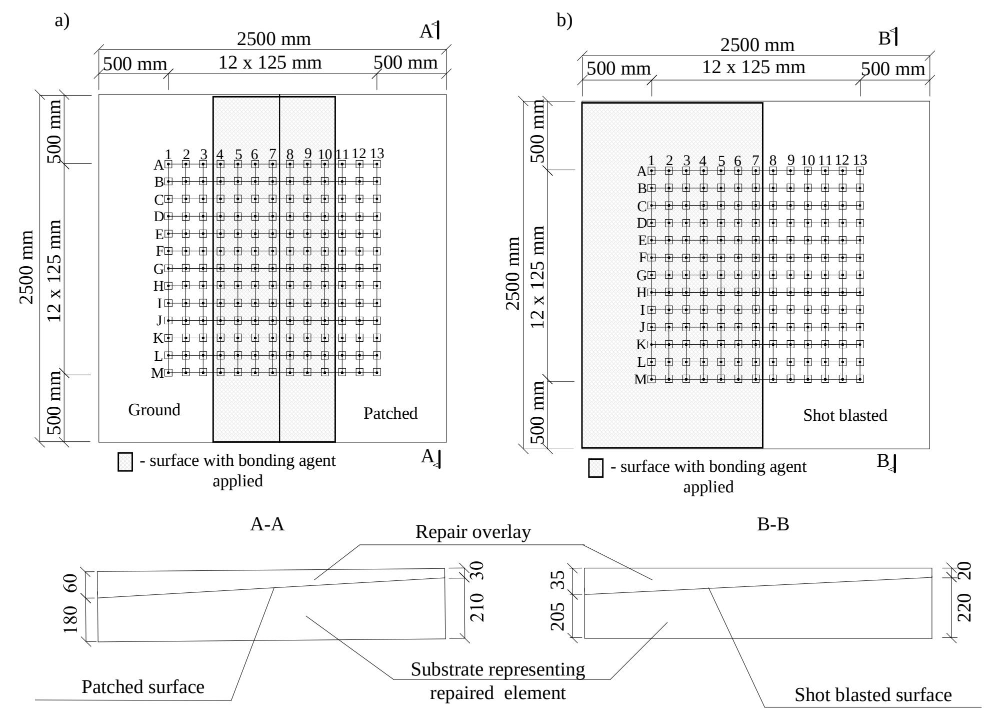

Fig. 1. Scheme of tested elements I (a) and II (b) with the distribution of measuring points

28 days after concreting the substrates of the elements, a grid of 338 measuring areas, 169 for each, was applied on their surfaces, as shown in Figure 1. In these places, tests using geometric leveling were then performed in order to later determine the thickness *T* of the applied repair overlay. Next, tests describing the morphology of both substrates using the three-dimensional scanning method were performed [7]. The results were obtained as three-dimensional

isometric views of a surface of 50 x 50 mm. Using specialized software, the obtained data was processed and in each of the measuring areas the values of the parameters describing the surface morphology, such as: 10 point height *S10z*, core height *Sk*, reduced peak height *Spk*, 5 point valley height *S5v*, closed hills area *Sha*, density of peaks *Spd*, closed hills volume *Shv*, 5 point peak height *S5p*, and closed dales volume *Sdv* were calculated. The exemplary values of these parameters are given in Table 1.

Table 1. Values of the parameters describing the surface morphology of the substrate.

Lp.	Number of element/ measuring area*	*S10z* [mm]	*Sk* [mm]	*Spk* [mm]	*S5v* [mm]	*Sha* [mm^2]	*Spd* [1/mm^2]	*Shv* [mm^3]	*S5p* [mm]	*Sdv* [mm^3]
1	I/M9	0,623	0,089	0,043	0,299	0,572	1,73	0,0075	0,324	0,0081
2	I/M10	0,857	0,087	0,045	0,312	0,782	1,25	0,0120	0,546	0,0123
3	I/M11	0,856	0,083	0,043	0,515	0,758	1,30	0,0086	0,341	0,0092
4	I/M12	0,677	0,079	0,042	0,296	0,469	2,10	0,0051	0,382	0,0053
					⋮					
337	II/A1	1,900	0,070	0,038	1,170	6,700	0,14	0,1340	0,729	0,0714
338	II/A2	2,270	0,072	0,037	1,440	7,690	0,12	0,1740	0,838	0,0994

* - designation of the measuring point, row and column according to Fig. 1

After applying the bonding agent, the repair overlay was applied on the surface of both elements. Then, after 28 days, a grid of measurement areas with an identical arrangement as on the surface of the substrate was applied on the surface of the repair overlay of both elements. In all of these places of both elements, the thickness of the applied repair overlay *T* was calculated by means of geometric leveling. Then, after 90 days, , non-destructive tests using impact-echo and impulse response methods were performed in these places, obtaining parameters such as: the frequency relating to the thickness of the element f_T, average mobility N_{av}, dynamic stiffness K_d, voids index *v*, and mobility slope M_p/N. The exemplary values of the parameters obtained on the repair overlay surface are given in Table 2.

Table 2. Values of the parameters obtained on the repair overlay surface.

Lp.	Number of element/ measuring area *	*T* [mm]	f_T [kHz]	N_{av} [m/s·N]	K_d [-]	*v* [-]	M_p/N [-]	f_b [MPa]
1	I/M9	65	8,79	27,3	0,058	0,943	2,580	1,452
2	I/M10	64	8,79	40,4	0,048	1,117	0,636	1,375
3	I/M11	66	8,79	54,6	0,031	0,902	0,358	1,477
4	I/M12	63	6,84	64,3	0,024	1,161	0,465	1,604
				⋮				
337	II/A1	22	8,79	33,3	0,072	0,696	0,777	3,056
338	II/A2	23	8,79	33,2	0,097	0,840	1,191	2,496

* - designation of the measuring point, row and column according to Fig. 1

After performing non-destructive tests, the real pull-off adhesion f_b values were determined in the same measuring areas using the pull-off method. The dataset, including 330 sets of results determined using non-destructive methods and parameter f_b obtained using the pull-off method, was then obtained. Then, in order to identify the value of the pull-off adhesion $f_{c,b}$, numerical analysis was performed. This analysis was performed using the artificial neural network multilayer perceptron [8, 9] with principal component analysis [10, 11].

3. Numerical analysis

The dataset, consisting of parameters obtained based on the experimental tests, was transformed by calculating the C_i components of the principal component analysis. For this purpose, the weights of the dataset parameters are used ($w_{11}, \dots, w_{nm}$) and the components were determined according to eq. (1), by [11]:

$$C_i = w_{11}(X_1) + w_{11}(X_2) + \cdots + w_{nm}(X_m), \tag{1}$$

where:

X_i – dataset parameter.

It was analysed how the variant transformation of parameters into components C_i of the principal component analysis affects the results obtained by the artificial neural network with the learning algorithm Broyden-Fletcher-Goldfarb-Shano [12] with 10 input parameters and 10 neurons of the hidden layer. Table 3 shows the results of analysis performed for over 40 variants of parameters, which were obtained based on the experimental tests. The results of learning and testing processes of the artificial neural network with principal component analysis, presented as mean values of the linear correlation coefficient *R*, are provided in the table.

Table 3. The results of learning and testing of the artificial neural network with principal component analysis for variants of the used parameters.

Symbols of the used parameters	Linear correlation coefficient value *R* [-] in the learning process	Linear correlation coefficient value *R* [-] in the testing process	Mean linear correlation coefficient value *R* [-] in the learning and testing processes
Spk, Sk, S10z, S5v, Sha, Spd, Shv	0,921	0,871	0,896
Spk, Sk, S10z, S5v, Sha, Spd, Shv, S5p	0,863	0,849	0,856
Spk, Sk, S10z, S5v, Sha, Spd, Shv, S5p, Sdv	0,853	0,843	0,848
Spk, Sk, S10z, S5v, Sha, Spd, T	0,922	0,829	0,876
Spk, Sk, S10z, S5v, Sha, Spd, Shv, T	0,911	0,844	0,878
Spk, Sk, S10z, S5v, Sha, Spd, Shv, S5p, T	0,900	0,854	0,877
Spk, Sk, S10z, S5v, Sha, Spd, Shv, S5p, Sdv, T	0,930	0,874	0,902
Spk, Sk, S10z, S5v, Sha, T, N_{av}	0,924	0,855	0,890
Spk, Sk, S10z, S5v, Sha, Spd, T, N_{av}	0,900	0,862	0,881
Spk, Sk, S10z, S5v, Sha, Spd, Shv, T, N_{av}	0,930	0,857	0,894
Spk, Sk, S10z, S5v, Sha, Spd, Shv, S5p, T, N_{av}	0,823	0,824	0,824
Spk, Sk, S10z, S5v, Sha, Spd, Shv, S5p, Sdv, T, N_{av}	0,870	0,855	0,863
Spk, Sk, S10z, S5v, T, N_{av}, K_d	0,934	0,863	0,899
Spk, Sk, S10z, S5v, Sha, T, N_{av}, K_d	0,864	0,874	0,869
Spk, Sk, S10z, S5v, Sha, Spd, T, N_{av}, K_d	0,942	0,866	0,904
Spk, Sk, S10z, S5v, Sha, Spd, Shv, T, N_{av}, K_d	0,923	0,877	0,900
Spk, Sk, S10z, S5v, Sha, Spd, Shv, S5p, T, N_{av}, K_d	0,845	0,859	0,852
Spk, Sk, S10z, S5v, Sha, Spd, Shv, S5p, Sdv, T, N_{av}, K_d	0,867	0,854	0,861
Spk, Sk, S10z, T, N_{av}, K_d, f_T	0,933	0,873	0,903
Spk, Sk, S10z, S5v, T, N_{av}, K_d, f_T	0,929	0,844	0,887
Spk, Sk, S10z, S5v, Sha, T, N_{av}, K_d, f_T	0,871	0,854	0,863
Spk, Sk, S10z, S5v, Sha, Spd, T, N_{av}, K_d, f_T	**0,928**	**0,885**	**0,907**
Spk, Sk, S10z, S5v, Sha, Spd, Shv, T, N_{av}, K_d, f_T	0,914	0,846	0,880
Spk, Sk, S10z, S5v, Sha, Spd, Shv, S5p, T N_{av}, K_d, f_T	0,882	0,848	0,865
Spk, Sk, S10z, S5v, Sha, Spd, Shv, S5p, Sdv, T, N_{av}, K_d, f_T	0,924	0,856	0,890
Spk, Sk, T, N_{av}, K_d, f_T, *v*	0,918	0,854	0,886
Spk, Sk, S10z, T, N_{av}, K_d, f_T, *v*	0,918	0,820	0,869
Spk, Sk, S10z, S5v, T, N_{av}, K_d, f_T, *v*	0,932	0,837	0,885
Spk, Sk, S10z, S5v, Sha, T, N_{av}, K_d, f_T, *v*	0,932	0,854	0,893
Spk, Sk, S10z, S5v, Sha, Spd, T, N_{av}, K_d, f_T, *v*	0,902	0,852	0,877
Spk, Sk, S10z, S5v, Sha, Spd, Shv, T, N_{av}, K_d, f_T, *v*	0,906	0,881	0,894
Spk, Sk, S10z, S5v, Sha, Spd, Shv, S5p, T, N_{av}, K_d, f_T, *v*	0,852	0,844	0,848
Spk, Sk, S10z, S5v, Sha, Spd, Shv, S5p, Sdv, T, N_{av}, K_d, f_T, *v*	0,932	0,872	0,902
Spk, T, N_{av}, K_d, f_T, *v, Mp/N*	0,874	0,860	0,867
Spk, Sk, T, N_{av}, K_d, f_T, *v, Mp/N*	0,929	0,839	0,884
Spk, Sk, S10z, T, N_{av}, K_d, f_T, *v, Mp/N*	0,922	0,872	0,897
Spk, Sk, S10z, S5v, T, N_{av}, K_d, f_T, *v, Mp/N*	0,912	0,837	0,875
Spk, Sk, S10z, S5v, Sha, T, N_{av}, K_d, f_T, *v, Mp/N*	0,924	0,861	0,893
Spk, Sk, S10z, S5v, Sha, Spd, T, N_{av}, K_d, f_T, *v, Mp/N*	0,918	0,857	0,888
Spk, Sk, S10z, S5v, Sha, Spd, Shv, T, N_{av}, K_d, f_T, *v, Mp/N*	0,924	0,871	0,898
Spk, Sk, S10z, S5v, Sha, Spd, Shv, S5p, T, N_{av}, K_d, f_T, *v, Mp/N*	0,864	0,843	0,854
Spk, Sk, S10z, S5v, Sha, Spd, Shv, S5p, Sdv, T, N_{av}, K_d, f_T, *v, Mp/N*	0,841	0,845	0,843

Based on the analysis of the results presented in Table 3, it was found that the values of the linear correlation coefficient for the learning and testing processes of the artificial neural network with principal component analysis and input parameters *Spk*, *Sk*, *S10z*, *S5v*, *Sha*, *Spd*, *T*, N_{av}, K_d and f_T are R = 0,928 for learning and R = 0,885 for testing. Moreover, the mean value of both processes is R = 0,907 and is the highest of those considered. The structure of the artificial neural network with principal component analysis for this variant is given in Figure 2.

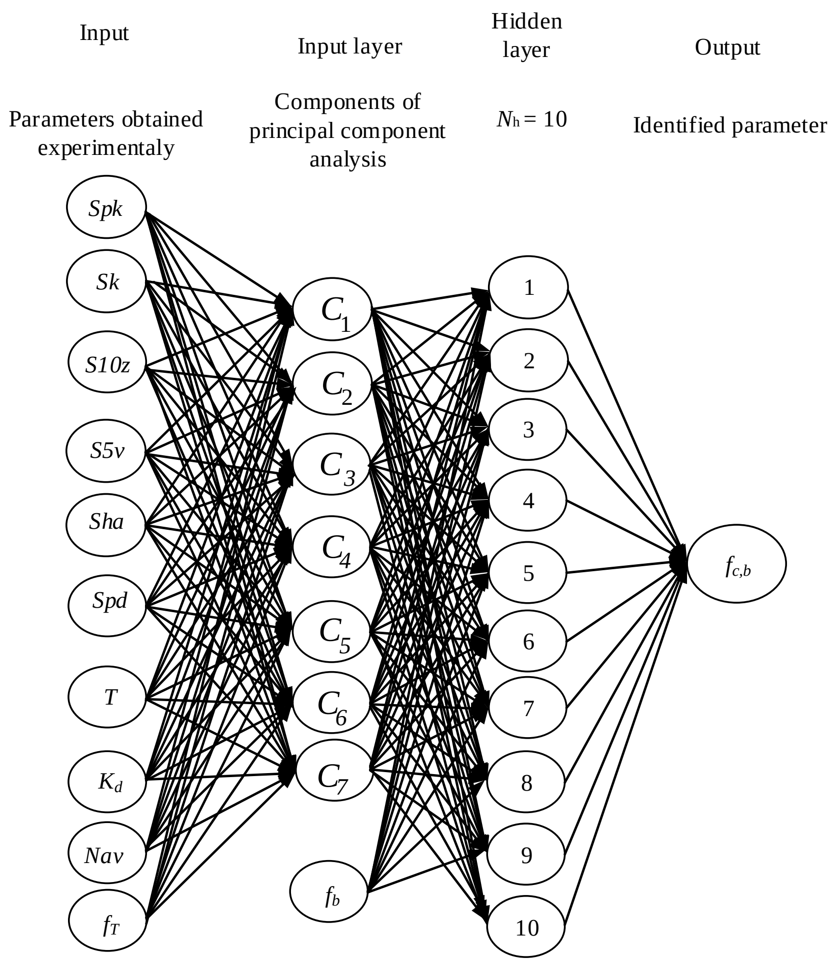

Fig. 2. Structure of the artificial neural network multilayer perceptron with principal component analysis

Figure 3 shows the relation between the pull-off adhesion $f_{c,b}$ value identified using the artificial neural network with principal component analysis, and the f_b value obtained from experimental tests using the pull-off method for the learning and testing processes.

Based on Figure 3, it was found that the artificial neural network with principal component analysis very accurately identifies the training data and also correctly identifies the testing data. This can be seen by the location of points along the regression line, corresponding to the ideal mapping and the obtained very high values of the linear correlation coefficient R, which are 0,928 for learning and 0,885 for testing.

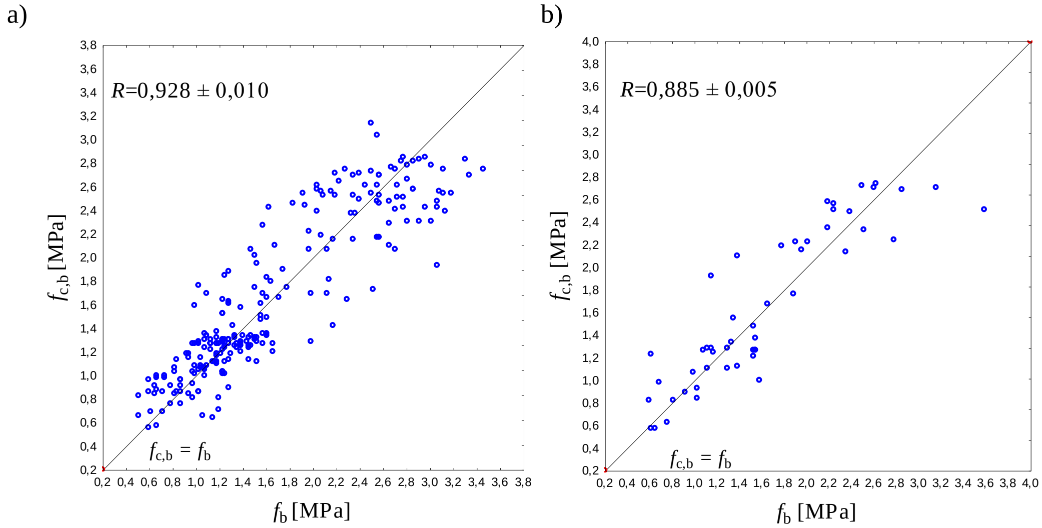

Fig. 3. Relation between the pull-off adhesion $f_{c,b}$ value identified using the artificial neural network with principal component analysis, and the f_b value obtained from experimental tests using the pull-off method for processes (a) learning and (b) testing

4. Conclusions

Based on the conducted research and numerical analysis, it was proved that identification of the interlayer bonding of concrete layers - the repair layer of variable thickness and the substrate layer - may be performed using complementary non-destructive methods and an artificial neural network with principal component analysis. It was shown that parameters describing substrate surface morphology obtained using the three-dimensional scanning laser method, parameters describing the thickness of the repair overlay, and parameters obtained using acoustic methods on the surface of the repair overlay are useful for this purpose. It was also shown that the artificial neural network with principal component analysis, learning algorithm Broyden-Fletcher-Goldfarb-Shano, 10 input parameters and 10 hidden layer neurons is most efficient for this purpose. This was proved by the very high value of the linear correlation coefficient for the learning process of R=0,928, as well as the high value for the testing process of R=0,885.

The presented method of identifying the pull-off adhesion value can be used in practice. This is due to the fact that it allows testing in any number of places without damaging the repair overlay. For this purpose, it is reasonable to perform verification on real objects.

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Monitoring of concrete placement and vibration for real-time quality control

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Abstract

This paper presents a conceptual framework for monitoring concrete placement and vibration operations. The proposed design is intended to enable collection and analysis of concrete pour data using computer vision and ultrasonic positioning. The system being developed alerts a project manager when workmanship observed is not in compliance with acceptable performance standards. The paper describes key operational factors in concrete placement and vibration that need to be monitored and reviews options for real-time locating systems. Fourteen factors related to concrete placement and their corresponding parameters are determined for measurement. In regard to the real-time locating systems, Ultra-wideband, ultrasonic, and computer vision technologies satisfy the expected levels of on-site positioning range and accuracy. Along with computer vision, ultrasonic technology has been chosen over Ultra-wideband alternative due to its lower cost and comparable performance.

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Keywords: concrete placement and vibration; quality control; real-time monitoring; workmanship

1. Introduction

Concrete placement and vibration are vital activities that turn site workmanship into an actual concrete product. Inappropriate placement and vibration adversely affect concrete quality and cause an onset and development of a concrete defect which increase direct and indirect costs of a construction project [1, 2]. A defect not only requires time and cost to correct, but it also increases the time spent by an inspector to examine, evaluate, and document the defect. Furthermore, defects may lead a contractor to penalty fees or legal disputes. These events not only cause loss in the current project, but also reduce opportunities to win future projects by damaging the contractor's reputation. Thus, it is necessary for contractors to reduce defects in order to save costs and secure competitiveness in the market.

However, previous efforts to procure quality concrete have focused mainly on enhancing defect management practices before/after site operations (e.g. material preparation and site inspection). Current operational practices on concrete still remain to be observed and managed by human supervisors, which is not a practical solution for all-time monitoring of compliance; supervisory control is sometimes lax since all managers are busy dealing with the work progress. Moreover, such method involves inconsistent measurement and assessment in assuring conformity of rules due to different levels of knowledge, field experiences and cognitive abilities of the managers. The dynamic environment of the construction site as well as a number of ongoing tasks and labourers make it even more difficult to achieve

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continuous and immaculate detection of poor workmanship. For these reasons, immediate and corrective actions are hardly made during the concrete operations. Instead, concrete defects are rather inspected and corrected after the concrete is already hardened.

Therefore, in order to help the managers to assure the quality of concrete operations and to proactively prevent the concrete defects, we propose a system designed to monitor the quality of workmanship in regard to concrete placement and vibration. The system will automatically collect data for concrete placement and vibration practices that may cause a quality issue. It will send an alert to a user (e.g. a manager and a superintendent) immediately when the concrete work-related parameters are out of the required range set by the user. This paper introduces the first part of our study in which we will 1) determine key operational factors (KOF) of concrete placement and vibration that play key roles in achieving concrete quality, and 2) investigate the appropriate real-time locating systems.

2. Current concrete work and defect inspection procedures

The general workflow of concrete activities and defect inspection is shown in Fig. 1. It involves the procedures that concrete is prepared, operated, and inspected in a project. During the entire course of concrete work and defect inspection, many tools have been developed and employed at multiple checkpoints as a safeguard so that any non-conformance is discovered, and a remedial action is taken.

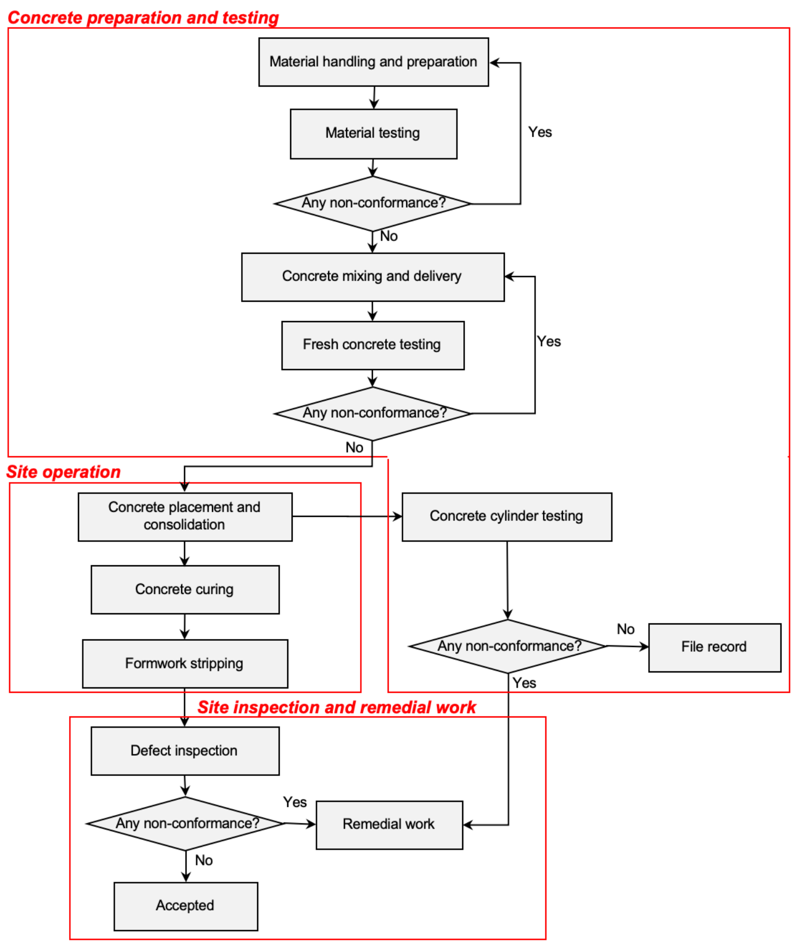

Fig. 1. Procedures for concrete placement and defect inspection.

The first stage is concrete preparation and testing. Materials for mixing concrete are prepared in this stage according to standard specifications. The individual materials used for a mix as well as the freshly mixed concrete are tested for quality assurance. At this pre-operational stage, it is common that provisions in a construction contract require a contractor and a supplier to comply with American Society for Testing and Materials (ASTM) standard specifications and testing methods [3, 4]. They introduce the procedures for measuring and preparing materials, sampling and testing methods of individual materials, and field testing of freshly mixed concrete.

When concrete is delivered to a site, a general contractor and subcontractors carry out on-site operations. During the operation, a site manager walks around to supervise whether the work practices are appropriate or not. There are manuals and guides which help to understand the standards and recommended operational practices. They serve as a reference by providing detailed information and instructions about concrete operations. For example, ACI 309R-96 Guide for consolidation of concrete introduces mechanism and methods of consolidation and recommended practices [5]. ACI 304R-00 Guide for measuring, mixing, transporting, and placing covers the recommended field practices on placing concrete in chapter 5 and the practices on concrete finishing in chapter 6 [6].

After stripping formwork, concrete is inspected to check whether the outcome quality satisfies all aesthetic and structural requirements. If an inspector finds a construction error or a defect, it will be reported to a project manager, and workers will be ordered to carry out remedial work. Many documents share information about concrete defect inspection based on which a project manager diagnoses the significance of a defect, plans a repair, and seeks for a way to prevent it [7, 8]. Besides, tools for automated inspection have been studied and developed to capture quality deviation quickly and accurately. Zhu et al. [9] introduced a method that utilizes image processing techniques for automated detection and measurement of surface air pockets on concrete. In the study of Radopoulou et al. [10], a framework that automates the process of acquiring data of defects on a road such as cracks, patches, and potholes was proposed. In addition to the inspection tools, there have been efforts in developing and improving defect management information systems to encourage utilization of detect data by streamlining data input, storage, and retrieval. These studies improved quality and security of defect data and enabled quick documentation. Kim et al. [11] provided a web-based defect inspection and management system with an apartment housing construction project. The defect data were acquired by using a Personal Digital Assistant (PDA) to fill a checklist at a site.

The review of the previous efforts indicates that there are not many hands-on tools and systems developed for controlling concrete operations and preventing concrete detects. Although proper concrete placement and vibration are essential to satisfy the quality requirements of a structure and to decrease the risk of reduced lifespan, just guides and manuals have been advised to be referenced. Faulty site workmanship and concrete defects are still common, resulting in numerous legal disputes. As long as the supervising concrete work remains to be conducted by human supervisors, observing noncompliance of the rules and the guides during work will be prone to errors and costly [2, 12]. The fact that all-time monitoring of site operations is not feasible with the current supervision method has led project managers to rely on a diagnostic and corrective approach, which is to inspect the quality of final components and repair a defect if observed. The truth is, an inspection is merely a method for detecting non-conformances ‘after-the-fact’, meaning that the management of defects by means of inspections is inherently reactive [2]. While corrective actions are very important to meet the desired final quality level, they are more costly than taking preventatives, and work results are often not as good as the originally planned quality [5, 13].

3. Methodology

We propose a conceptual framework to monitor the quality of workmanship in real-time and to alert a manager/superintendent when concrete work-related parameters are unacceptable. To develop the framework, this section determines key operational factors and investigates real-time locating systems. This study focuses on concrete placement with a concrete pump car (also known as a truck-mounted mobile pump) and consolidation with an internal concrete vibrator (also as known as a spud or poker vibrator), both of which are commonly used at construction sites.

3.1. Determining key operational factors (KOFs)

Various documents such as books, websites, articles, reports, journal papers, and guides about workmanship and concrete defects were reviewed to determine the key operational factors (KOFs) which represent the critical workmanship to concrete quality. Then, their parameters were investigated to clarify the objects and motions of interest regarding each KOF. Such parameter gives a better insight into how to measure the KOF and how to determine its violation. Table 1 summarizes the fourteen workmanship factors and their parameters.

Table 1. Key operational factors and their parameters

	Key operational factor (KOF)	Parameter
1	Crews should deposit only as much concrete as can be consolidated efficiently	Depth of freshly placed concrete layer Duration that a pump hose stays at one place
2	Placement should continue before a cold joint develops. Compaction must be done while concrete is still plastic	Time gap of placement between layers Time gap between placement and vibration
3	Placing concrete should be from an appropriate height	Height of the discharging point at pump hoses
4	Concrete should drop vertically	Angle of the discharging point at pump hoses Angle between the discharging point at pump hoses and deposited location of concrete
5	Concrete should not be placed directly on reinforcing bars	Area that dropping concrete touches rebar
6	Concrete should be vibrated for an appropriate duration	Duration that a vibrator tip stays as inserted into concrete
7	Vibration sticks should be inserted to the sufficient depth	Depth of a vibrator's insertion into concrete
8	Distance between insertions of the vibrator head should be appropriate	Distance between insertions
9	Vibrators should be kept close of the form face to avoid defects from insufficient vibration	Distance between forms (where concrete is placed) and their closest insertion
10	Vibrators should not be allowed to touch the forms	Duration that a vibrator is touching a form
11	Vibrators should not be held against the reinforcement	Duration that a vibrator is touching a reinforcing bar
12	Vibrators should quickly penetrate the concrete layer and be removed slowly to remove entrapped air	Vibrator's insertion/withdrawal speeds
13	Vibrators should be inserted and withdrawn vertically	Angle of the vibrator when inserted/withdrawn
14	Dragging vibrator through the concrete should be prohibited	Distance of a vibrator's horizontal movement while inserted

3.2. Review of real-time locating systems (RTLS)

Real-time locating system (RTLS) is a system which continuously determines a position of an object in real-time. In order to choose the best approach for the addressed problem, possible options for RTLS and their fundamental capabilities were reviewed and compared. Table 2 was excerpted and updated from the studies of Karunaratne et al. [14] and Gong et al. [15].

Table 2. Comparison of real-time locating systems (RTLS).

RTLS	Description	Reading range	Accuracy
GPS	A space-based satellite navigation system that allows a GPS receiver to calculate its position by precisely timing the signals sent by GPS satellites high above the Earth.	Used where satellite signals reach [16]	0.01 m with differential GPS 2-5 m others
RFID	A technology that uses radio waves as a way of identifying, locating, and tracking objects.	Passive 10 m Active 100 m	1–3 m
Infrared (IR)	A technology that uses diffused IR to achieve room-level locating.	10 m	5–10 m
Wi-Fi (IEEE 802.11)	A technology that relies on 802.11 networking for real-time locating.	100 m	1–5 m
Zigbee (IEEE 802.15.4)	A technology that operates based on the IEEE 802.15.4 standard for localization.	10–100 m	1 m
Ultra-wideband (UWB)	A technology that uses radio waves with large band widths to track radio tags.	30 m	0.01 m
Cellular RTLS	The cellular-based RTLS relies on resolving the position of the mobile device by indicating the cell with which the mobile device is registered.	Can be used where cellular networks are available	50–200 m
Computer Vision	A technology for detecting objects in an image and recognizing the object in successive video frames.	Visible distance	A few centimetres
Ultrasonic	A technology that uses ultrasonic pulses to calculate receiver's position.	* 30m	0.02 m [17]

Electromagnetic	A technology that enables localization of small electromagnetic sensors in an electromagnetic field without line-of-sight [18].	** 15 feet	*** 0.013 m

* Data obtained from a product manual by Marvelmind [19].
** Ascension 3DG sensors: up to 10 feet [20] and Polhemus micro sensor: up to 15 feet (G4) [21]
*** https://polhemus.com/_assets/img/G4_Brochure.pdf

In order to measure the parameters of KOFs accurately and instantly, we determined that the minimum reading range as 10 metres, and an error is expected to be lower than 10 centimetres to avoid misinterpretations or wrong decisions. Ultra-wideband (UWB), ultrasonic (US) and computer vision are considered to meet our needs in terms of the reading range and the accuracy. While UWB and US have similar mechanisms of calculating positions, performance and output datatype, US systems are less expensive than UWB systems. Therefore, along with computer vision, US was chosen over UWB due to its cost-effectiveness.

3.3. Ultrasound positioning system

Ultrasonic positioning system utilizes ultrasonic waves that have higher frequencies than the audible limit of human hearing to get a tag's location [14]. The tag attached to an object emits a unique ultrasonic signal, and the signal is sensed by receivers. The tag's location can be figured out using the information of the signal such as speed, departure time and arrival time. Ultrasonic positioning system has many advantages which made it gain popularity. Ultrasound waves cannot penetrate walls and are negligibly affected by the surroundings, they which means that the system is not disturbed by ultrasonic waves in other rooms [16]. It provides with centimetre-level accuracy with a low system cost, and it can track multiple mobile nodes simultaneously [22]. However, though it is scalable, room-level applications are typical because the cost increases as a larger area is covered. In addition, its performance can be influenced largely by the environmental conditions such as humidity and temperature [23]. Ultrasonic signals quickly fade away and travel a short distance when humidity is high, and the speed of the signal is directly affected by temperature. Many devices attempt to offset these effects by integrating it with a temperature or a humidity sensor. External noises could be another problem to its accuracy, but they are often low-frequency and can be filtered by algorithms [22].

Ultrasound waves have been widely used in the construction field. Zhou et al. [24] developed an Internet-of-Things-based system to achieve improved safety for underground construction sites. They installed ultrasonic detectors which have the centimetre-level accuracy to construction vehicles such as excavators and dump trucks to improve safety. Lee et al. [25] developed a mobile safety monitoring system which senses human and inanimate objects by utilizing ultrasonic and infrared sensors. The previous applications were mostly to measure distances between two points, not to get three-dimensional coordinates in a space.

3.4. Computer vision

Computer-vision is the theory and technology for understanding how computers can be made to gain high-level understanding from digital images or videos [26]. Today, as more images and videos are obtained and shared, a vast amount of information can be extracted and used by computer vision. Computer vision RTLS is useful especially when it is not practical to attach a tag to an object. While other systems such as RFID can gather locational information for objects, computer vision technology enables to extract additional information such as size, colour, and texture of an object. Since it saves visual data in pixels, long range recognition is viable as long as the resolution is high and the sight is clean. However, the instrument cost for entire RTLS can be expensive when it involves high-resolution cameras and computers equipped with powerful central and graphics processing units. Its accuracy can vary depending on the image resolution and visibility. Besides, the sizes of images or videos are usually large, so transferring them to a computer may require a high speed of network.

There are two different approaches in terms of object detection in computer vision: 1) traditional machine-learning-based and 2) deep-learning-based. The traditional approach employs hand-coding to extract certain features of an

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object using feature descriptors. Feature extraction is to reduce the image information to a feature vector which represents unique and identifiable parts of the image [27]. For example, Sobel detectors are used for edge detection while Laplacian of Gaussian (LoG) is used for blob detection (Fig. 2). After that, a machine learning tool is used to determine whether the observed object is classified as the trained object. On the other hand, the deep-learning approaches such as R-CNN and YOLO use neural networks to extract and learn useful representations of features directly from the data [28]. In these approaches, the model learns by itself to select the best-performing filters to detect objects. They have become more powerful and shown successful applications in many fields such as a self-driving car.

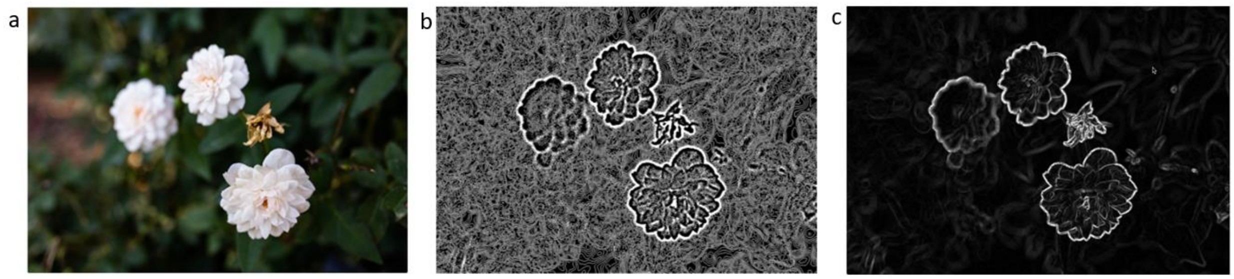

Fig. 2. Examples of feature descriptors. (a) original; (b) Laplacian of Gaussian (LoG); (c) Sobel.

The next application is object tracking, which is to find an object in a current frame assuming that the object has been tracked successfully in the previous frames. It is different from a mere repetition of detection because some information such as location, direction, and speed of motion captured from the previous frames can be used for tracking objects in successive frames. Unlike object detection, object tracking does not necessarily identify the objects to be tracked because it leverages the relationship between successive image frames. This can allow object tracking algorithms more computationally cheaper and efficient than running object detection repetitively. One of the popular object tracking algorithms is the Meanshift tracker (Fig. 3 (a)). It uses histograms of an object in the current image to figure out its location in the next image frame by minimizing the distance between two probability density functions [29]. Background subtraction algorithms are also useful to extract an image's foreground when using stationary cameras (Fig. 3. (b)).

In addition to object detection and tracking, computer vision includes the domain of 3D analysis from 2D images, which is called as stereo vision. Given two or more images of the same scene, its 3D shape can be represented. Implementation of stereo vision is necessary to get 3D location data of the object detected or tracked in an image. In multi-view stereo vision, two or more cameras are displaced at known locations and orientations, and they look at a same scene. Then, a disparity of features between the stereo images are used to calculate the distance. Fig. 3. (c) shows an example of binocular stereo vision. The depth information is extracted by comparing left-view and right-view images.

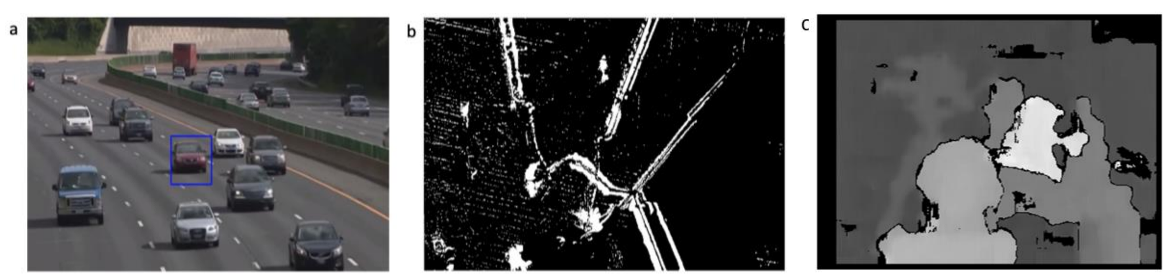

Fig. 3. (a) Meanshift tracker applied to car tracking [30]; (b) background subtraction applied to a video clip [31]; (c) example of stereo vision (depth map) [32].

Many of the reviewed studies of concrete inspection systems are the examples of object detection using computer vision. Not only concrete, but also other materials such as timber and steel were recognized and inspected [33, 34]. Background subtraction algorithms have been employed for reliable detection and tracking of objects. Chi et al. [35]

introduced a method for detection and recognition of heavy equipment and workers, which employed classifiers and background subtraction algorithms to recognize objects from videos. Yang et al. [36] developed a vision-based system for assessing crane activities. They used a background subtraction algorithm to segment the crane from other elements. Stereo vision has mostly been used for automation of updating and monitoring progress of a project. Bugler et al. [37] presented a method for estimating an activity status and progress of an excavation work. By using feature-based stereo, they created a 3D point cloud of a site space from images taken from an unmanned aerial vehicle (UAV) and estimated the excavated volume.

3.5. Conceptual framework of the system

The conceptual framework and flow of implementing the system is presented in Fig. 4. The system performs data collection on concrete placement and vibration activities from three different sources: 3D model, ultrasonic positioning sensors and tags, and a pair of cameras. A 3D model contains information such as locations of forms and reinforcing bars, a space name, compartment, and a concrete element type. Ultrasonic devices and computer vision are responsible for collecting information of moving objects. Both can track locations of objects, but computer vision can be also used to estimate an activity status in addition to the locations. For example, it can detect the status of placement activity by checking whether concrete is dropping from the hose or not. Workmanship is monitored based on the information collected from the three sources, and the system immediately alerts the site manager when this information indicates that the workmanship is faulty and unacceptable.

The first step of system implementation includes acquisition of a 3D model, installation of a pair of cameras and ultrasonic sensors, and camera calibration. Cameras and ultrasonic positioning system should be installed where the scene can be recorded with minimum occlusion because they may lose accuracy of detecting or tracking an object when it is partially or entirely occluded. After completing calibration of cameras, conversion matrices need to be calculated from each system to integrate different coordinate systems. This can be done by comparing a set of points collected from different sources and calculating coordinate conversion matrices. When all devices are set up and conversion matrices are known, object locations during concrete placement and vibration are collected. The data are continuously compared to the thresholds of KOFs set by a manager to make sure they are within an acceptable range. If a violation is detected, the system extracts and compiles the violation data and sends a warning message to the manager. The data are trimmed and organized so that the manager can understand the issue quickly and accurately. Visualized location data with graphs and statistical summary is attached to a warning message in order to facilitate comprehension and communication of stakeholders.

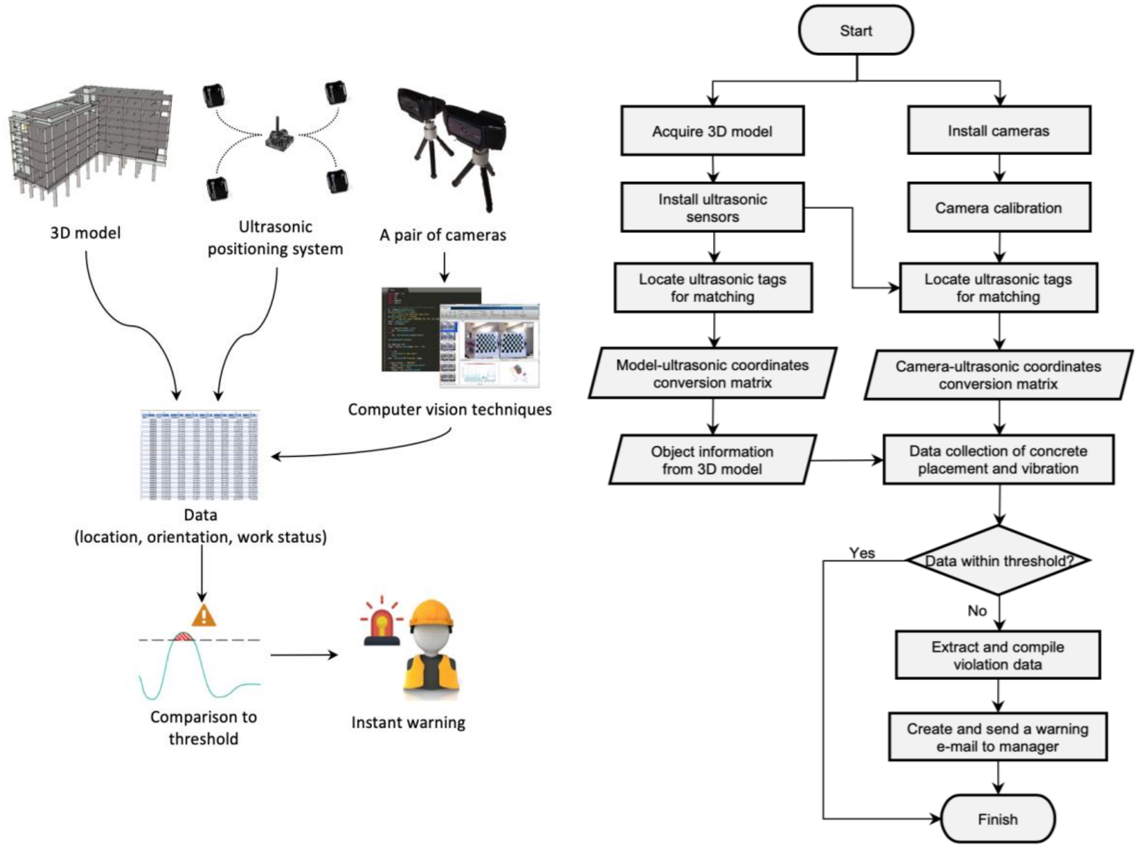

Fig. 4. (a) conceptual framework of the proposed system; (b) flow of implementation

CONCLUSION

The needs for real-time monitoring of concrete workmanship have arisen to overcome the inefficiency and inaccuracy of the current supervising method. To provide managers with timely and appropriate data as a proactive and preventive approach, this paper introduced the conceptual framework and implementation flow of an automated system for monitoring concrete placement and vibration work. Fourteen KOFs and their parameters were determined by examining document about workmanship and concrete defects. Then, RTLS were reviewed and selected by comparing their reading range and accuracy. We determined to utilize ultrasonic and computer vision with the information extracted from a 3D model. Lastly, the conceptual framework and implementation flow of the proposed system are introduced. The remaining steps include the full-scale development and testing of the system. A mock-up experiment at a testbed is planned at the University of Maryland to perform data acquisition and test reliability of the system. Ultrasonic positioning system will be tested to check if any condition decreases data accuracy or acquisition rate. In regard to computer vision, algorithms for object detection and tracking will be tested. Besides, the accuracy of stereo vision will be evaluated by comparing the actual measurement and the estimated position from the cameras. Technical and practical difficulties will be addressed after the test, and their potential solutions will be explored.

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Non-destructive in situ identification of the moisture content in saline brick walls using artificial neural networks

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Abstract

The article proposes a method of neuron identification of the moisture content in saline brick walls of historic buildings, carried out on the basis of non-destructive testing. The method is based on the use of artificial neural networks, which were trained, tested and experimentally verified on a set of data constructed for this purpose. The set consists of test results that were obtained using non-destructive methods on a selected representative group of historic masonry buildings. Based on numerical analyzes, an appropriate type and structure of the ANN and learning algorithm were selected. Positive results were obtained, which indicated the possibility of using the proposed method in practice.

Keywords: budynki zabytkowe, mury ceglane, wilgotność, badania nieniszczące, sztuczne sieci neuronowe

1. Introduction

Maintaining the appropriate condition of historic buildings, which are testimonies of past epochs, is of significant social interest due to their artistic and historical value. In order to keep these building objects in good condition, various technical problems must be faced, including one of the most common - the excessive moisture of walls. This moisture is caused by the lack of damp-proof insulation that was not previously executed [1-3]. Long-lasting direct contact of a wall with the ground causes water molecules that are contained in the ground, along with the salts dissolved in them, to gradually penetrate into the components of the wall, while at the same time dampening and salting them. This contributes to moisture destruction [4-5] that progresses over time, the exemplary effects of which are shown in Figure 1. The negative effects of excessive moisture are compounded by the destructive effects of water-soluble salts. As a result of the crystallization and hydration processes that take place in the sub-surface zone of a wall - in the capillaries and pores - and on its surface, salts break up the masonry structure and form surface salt efflorescence [5-7].

Before conducting conservation actions that lead to the stopping of the above-mentioned destructive processes, and consequently the preserving of historic tissue in an appropriate condition, it is necessary to carry out tests that aim to determine the size and causes of the moisture content and salinity.

In literature [8-12], it has often been signaled that among all the known methods of testing the moisture content in brick walls, the most reliable results are obtained by the gravimetric method. This allows the moisture content values to be determined on the surface, as well as along the thickness of the tested partition. During its use, however, it is

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necessary to take in situ samples of material for laboratory tests, which in the case of historic building objects is usually only possible to a very limited extent. In the case of evaluating salinity, the possibilities are greater because interference with the wall is minimal. This is due to the fact that only small samples of a few grams are taken for testing from the subsurface zone where the salt content is the largest. Due to this limitation, non-destructive methods are predisposed to perform tests of the moisture content in brick walls of historic buildings. However, they also have some limitations in their usage and require so-called scaling, which is discussed later in the article. The ignorance of their specificity may lead to unreliable results being obtained.

Fig. 1. Moisture destruction of a brick wall in a historic building

Bearing in mind the above, the aim of the article is to propose a neural non-destructive method for assessing the moisture content in the saline brick walls of historic buildings. It eliminates, to the maximum extent, the necessity of interfering with the historical tissue of a building object, which is unavoidable in the case of testing the moisture content using the gravimetric method. It also eliminates the need to scale apparatus each time it is used for non-destructive testing, which is necessary for the correct interpretation of results.

The proposed method of assessment is based on the use of artificial neural networks, which are trained, tested and experimentally verified on a data set that was constructed for this purpose. This set consists of the results of tests that were obtained on a representative group of historic brick buildings erected in different historical periods. It is assumed that the network that is trained on this set, after the experimental verification carried out on other historic buildings, will be useful for the correct identification of the moisture content of saline walls. This identification will be conducted with minimal interference in the wall structure, and be based on the carried out non-destructive tests. The data set contains two parameters that are determined using non-destructive methods - dielectric and microwave - and three parameters that describe the concentration of basic salts found in the damp walls, which are indicated using the semi-quantitative method. The usefulness of this approach regarding in situ objects was confirmed on the basis of tests carried out in laboratory conditions [13]. This publication presents the effects of work in the form of a constructed data set that consists of the above-mentioned parameters, as well as the results of training, testing and experimental verification of the selected artificial neural network.

2. Methodology of testing

In order to build a set of data for the purpose of training, testing and experimentally verifying artificial neural networks, in-situ investigations of the moisture content in brick walls were carried out in a few selected historic buildings. These buildings were erected in different years and historical periods and were made of full ceramic brick and lime mortar. The mentioned representativeness is manifested in the fact that the obtained results of the tests of the moisture content and wall salinity are within wide ranges. In each of the building objects, measuring points were selected in various, but similar to each other, amounts, which was required by the conservation services. The list of building objects is shown in Table 1.

More than 200 sets of results were included in the data set. Each set consists of six parameters: two dimensionless that describe the moisture content of a wall, and three that describe the molar concentration of the three basic salts that can be found in the tested brick walls (nitrates, chlorides, sulphates). The above-mentioned parameters were obtained from tests that used two non-destructive electric methods: the dielectric method with the use of the GANN UNI 2 dielectric meter with a ball probe, and the microwave method with the use of the T600 microwave meter. From each of the measuring points, a specimen was collected for gravimetric tests in order to determine the salt concentration using the semi-quantitative method, and also to determine the real mass moisture content U_m, which is the sixth parameter that is necessary to train an ANN.

Table 1. Basic information about the buildings in which tests were conducted in order to build a data set

No.	Building description	
1.	Name, location	monastery of the Benedictine Abbey, Pomerania, Poland
	Construction date	the turn of the thirteenth and fourteenth centuries
	Description of the building object	erected according to the classical scheme of the Cistercian monastery that is based on a quadrangle of buildings gathered around a patio surrounded by cloisters
	Place of conducting measurements	▪ basement rooms under the northern wing of the monastery ▪ wall thickness ranging from ~ 60 cm to ~ 180 cm
2.	Name, location	pavilion at Wzgorze Partyzantow, Wroclaw, Poland
	Construction date	XVI - XIX century
	Description of the building object	▪ erected in the place of the former bastion ▪ located at the foot of a hill; some of its external walls are partially covered with soil ▪ a single-storey building kept in a style that refers to the Italian Renaissance
	Place of conducting measurements	▪ internal and external walls that are in contact with the ground, and also the ones that are not in contact with the ground ▪ wall thickness of about ~ 85 cm
3.	Name, location	building of the Heimann Foundation, Wroclaw, Poland
	Construction date	XIX wiek
	Description of the building object	▪ erected by the foundation of Wroclaw bankers E. and H. Heimann as a nursing home for the poor inhabitants of Wrocław ▪ a three-storey building in a style that refers to the Middle Ages
	Place of conducting measurements	▪ external walls of basement rooms ▪ wall thickness of about ~ 60 cm to ~ 80 cm
4.	Name, location	residential building, Nowa Ruda, Poland
	Construction date	XIX century
	Description of the building object	▪ the building has a basement under a part of it and three above-ground storeys
	Place of conducting measurements	▪ external and internal walls of the basement rooms and ground floor ▪ wall thickness of about ~ 50 cm
5.	Name, location	administrative building, Wroclaw, Poland
	Construction date	the end of the 19th century
	Description of the building object	▪ the building has a basement and four above-ground storeys ▪ wall thickness of about ~ 80 cm
	Place of conducting measurements	▪ external walls of the basement rooms

3. Test results

Table 2 contains part of the data set consisting of a total of 205 sets of results. Each set has two dimensionless parameters - X_D and X_M - which were determined non-destructively using the dielectric and microwave methods, respectively; three parameters X_A, X_C, and X_S that describe the molar concentrations (in %) of nitrate, chloride and sulphate salts, which were determined using the semi-quantitative method; and also parameter U_m that describes the real mass moisture content of the wall (in %), which was obtained using the gravimetric method. From the obtained data set, 145 randomly selected sets of results were designated for training, 31 were randomly selected for testing, and 29 were randomly selected for experimental verification of the artificial neural network.

Table 2. Data set

Data set number [-]	Parameter describing the moisture content, which was determined using the dielectric method X_D [-]	Parameter describing the moisture content, which was determined using the microwave method X_M [-]	Parameter describing the molar concentration of nitrate salts in the wall X_A [%]	Parameter describing the molar concentration of chloride salts in the wall X_C [%]	Parameter describing the molar concentration of sulphate salts in the wall X_S [%]	Parameter describing the real mass moisture content of the wall U_m [%]
1	133,8	74,0	0,033	0,250	0,000	8,45
2	74,5	33,2	0,035	0,300	0,000	1,84
3	121,6	34,5	0,055	0,300	0,010	6,25
4	131,7	43,2	0,060	0,350	0,100	4,48
5	104,4	33,3	0,045	0,300	0,025	1,52
6	141,9	24,5	0,048	0,200	0,010	5,77
7	120,7	25,5	0,047	0,250	0,000	2,65
8	63,0	26,4	0,040	0,200	0,000	1,39
9	129,5	34,6	0,025	0,250	0,000	4,07
10	93,3	30,3	0,022	0,250	0,000	2,17
11	64,7	29,6	0,037	0,300	0,010	3,67
12	95,8	33,4	0,022	0,200	0,000	4,06
13	97,6	27,5	0,020	0,200	0,000	3,61
14	88,6	30,0	0,032	0,250	0,000	2,75
15	81,0	29,8	0,030	0,250	0,000	4,11
16	120,5	35,5	0,029	0,250	0,000	8,69
17	48,5	22,0	0,040	0,250	0,000	1,65
18	140,8	41,4	0,098	0,300	0,025	5,48
19	105,2	33,5	0,018	0,200	0,000	3,39
20	62,0	30,7	0,040	0,200	0,000	2,51
21	75,3	27,0	0,056	0,200	0,000	3,94
22	47,9	24,1	0,020	0,200	0,000	0,98
23	77,9	31,6	0,034	0,200	0,000	3,80
24	46,6	29,0	0,049	0,250	0,000	1,74
25	55,0	30,9	0,035	0,300	0,000	1,56
26	78,3	33,2	0,039	0,250	0,025	1,88
27	41,3	28,5	0,030	0,200	0,000	1,29
28	103,6	31,8	0,032	0,200	0,000	1,60
29	76,7	37,2	0,070	0,350	0,025	1,82
30	70,8	30,4	0,030	0,250	0,010	1,22
.	.	.	.	.	.	.
205	121,6	34,5	0,055	0,300	0,010	6,25

4. Numerical analysis

A unidirectional multilayer artificial neural network with back-propagation error, the conjugate gradient (CG) algorithm, and the number of hidden layer neurons equal to 3 was selected for the purpose of training and testing in order to non-destructively identify the value of the moisture content U_{mc}. Figure 2 shows the relationship between the real moisture content U_m that was obtained using the gravimetric method, and the moisture content U_{mc} that was identified by the unidirectional multilayer artificial neural network with back-propagation error, the conjugate gradient

(CG) algorithm, the number of hidden layer neurons equal to 3, and the number of epochs equal to 150. Figure 2a shows this dependence for the training process, while Figure 2b shows it for the testing process. From Figure 2a it can be concluded that the network correctly maps the training data and correctly identifies the testing data. This is evidenced by the location of points along the regression line that corresponds to the ideal mapping and the high values of the linear correlation coefficient R that are equal to 0.919 and 0.928 for the training process and testing process, respectively.

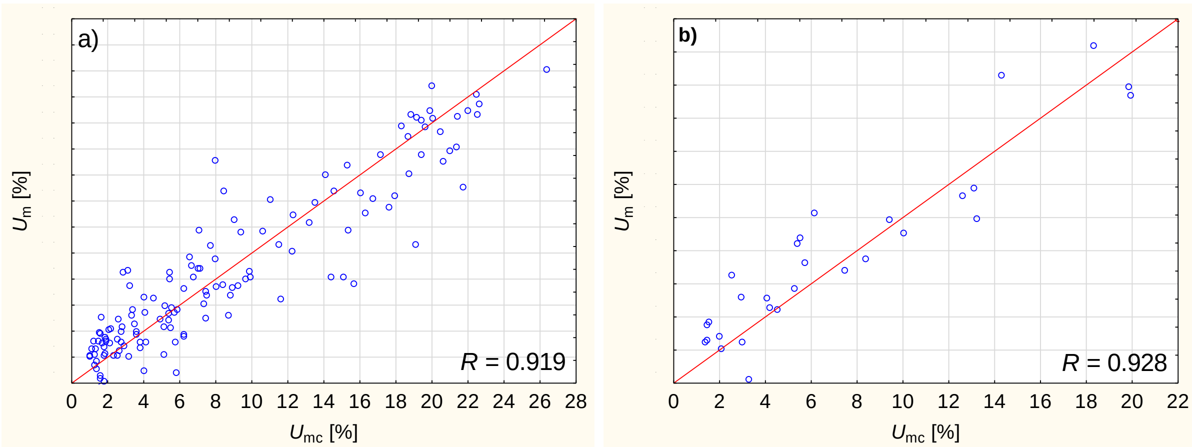

Fig. 2. Relationship between the mass moisture content Um of the tested walls that was obtained using the gravimetric method, and the moisture content U_{mc} that was identified by the network for the process of: a) training; b) testing

In turn, Figure 3 shows the relationship between the moisture content U_m that was obtained on the basis of experimental tests, and the moisture content U_{mc} that was identified by the network for the process of experimental verification. The obtained results show that the network correctly maps randomly selected verification data. This is confirmed by the location of points along the regression line, which corresponds to the ideal mapping, as well as by the obtained high value of the linear correlation coefficient R, which is equal to 0.906.

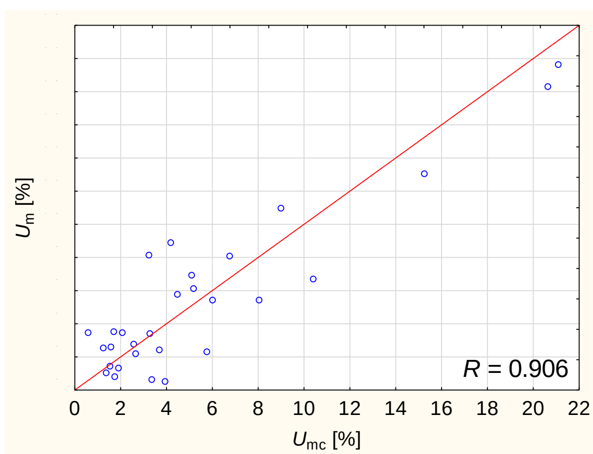

Fig. 3. The relationship between the mass moisture content U_m that was obtained on the basis of experimental tests, and the moisture content U_{mc} that was identified by the ANN for experimental verification

5. Summary

On the basis of the conducted moisture content tests of saline brick walls in five historic buildings, a data set consisting of more than two hundred sets of results was built. Each set has six parameters: two that describe the moisture content assessed using non-destructive dielectric and microwave methods, three that describe the salinity assessed using the semi-quantitative method, and also the mass moisture content evaluated using the gravimetric method. This set was used for training, testing and experimental verification of a selected unidirectional multilayer artificial neural network with back-propagation error, which was chosen for the purpose of identifying the moisture content of brick walls in buildings that are historically valuable.

The carried out numerical analyses proved that it is possible to reliably identify the moisture content of saline brick walls using artificial neural networks that have an appropriately selected structure and learning algorithm based on the parameters from which the data set was created. A unidirectional multilayer artificial neural network with back-propagation error and the conjugate gradient algorithm is predisposed for this purpose. This is evidenced by the obtained high values of the linear correlation coefficient R of 0.919, 0.928 and 0.906 for the training, testing and experimental verification processes, respectively.

The proposed neuronal method of assessing the moisture content based on parameters evaluated using non-destructive methods, despite the obtained positive result of experimental verification in numerical analyses of the above-mentioned artificial neural network, still requires verification on other historic buildings. These works are currently being carried out. After their completion, it will be possible to more often use the described method in construction practice.

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A Review of Studies in Structural Health Monitoring (SHM)

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Abstract

India is a country of diversity not only in terms of culture and population but also in terms of landscape ranging from snow-capped mountains to desserts, plateaus, plains and hills. The climatic conditions in India vary from extremely hot to extremely cold resulting in the requirement of different types of constructions in each region subjected to its temperature, geographical and climate conditions. India is a county where thousands of years old buildings are still standing strong despite several changes in various factors over the years, whereas a few years old building collapses more easily, which raises the most important question in our mind regarding the Structural health of buildings over the years and how Well structure health monitoring is done in India. Structural Health Monitoring is defined as a process of identification of damage for aerospace, mechanical and civil infrastructure. Performance of the structures are determined by various factors such as the age of the building, material used, service condition and layout of the structure besides performance, safety, reliability and serviceability are also the crucial points. SHM technology is implemented in various countries like Europe, USA, Korea, Japan etc. for monitoring of large structures. The main aim behind the implementation of SHM is to determine the damage during initiation itself so that the further damage propagation can be ceased by an alarm in the initial stage with the help of continuous monitoring by structurally integrated sensors.

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Keywords: SHM; Building Construction; Technology; India; Construction Management; Building Material.

1. Introduction

Over the years construction industry has observed a huge change in the methods adopted for the construction. From the use of natural materials for construction to the use of composite materials for specific construction, Construction industry has seen a continuous trend of simple to complex construction. After completion of the construction these structures are exposed to various conditions resulting in its deterioration. Every structure deteriorate with the passage of time. There are various reasons due to which structure deteriorates for example repetitive traffic load, any natural calamity etc., which in turn reduces the margin of safety and the serviceability span of the structure resulting in the loss of life and structure. The main aim of SHM is to give the diagnosis of the state, at every movement of the life cycle of the structure. The process of implementation of the strategy to detect the damage is known as Structural Health Monitoring (SHM). SHM is used for rapid condition screening and aims to provide, in near real time, reliable information regarding the integrity of the structure.

1.1 SHM

I. Health Monitoring

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II. Operational Evaluation

III. Data Feature Extraction

IV. Statistical Models Development

First and the foremost step of SHM is to identify the damage, then determine the geometric location of the damage, after that quantification of damage severity is done and lastly the remaining life of the structure is predicted. Following are the objectives of the SHM:-

I. How to improve the performance of the existing structure.

II. Monitoring of structures affected by external factors.

III. To provide feedback in order to improve the design for future.

IV. Assessment of structural integrity after the earthquake.

When the structure is embedded with the sensors for the monitoring it is called as Passive SHM and when the structure is embedded with sensors as well as actuators in order to generate perturbations in the structure, to see its response it is called as Active SHM. Following are the SHM techniques:-

I. Vibration based technique

II. Fibre - Optic Sensors

III. SHM with Piezoelectric Sensors

IV. SHM using Electrical Resistance

V. Low Frequency Electromagnetic Techniques

VI. Capacitive Methods for SHM in Civil Engineering

Damage can be identified by two ways which are Global and Local. When the whole structure is assessed simultaneously it is known as Global Damage Detection. And when the non-destructive evaluation tool focus on a specific component of a structure it is called as Local Damage Detection.

2. Literature review

[1] Provide one of the most comprehensive reviews of the technical literature concerning the detection, location, and characterization of structural damage through techniques that examine changes in measured structural-vibration response. [2] Talks about the limitations associated with the SHM. According to them to identify the damage on the basis of realistic data set is far away from the reality with robust identification technique. [3]cite some critical issues for SHM, particularly with civil infrastructure, which need to be resolved for deploying reliable SHM systems. According to the Author combination of integrated approach, between government, academia and industry is required, and engineering approach irrespective of the engineering branch is needed to sort out the issues related to SHM. The author focuses on the following requirements to improve SHM:-

a. Organizations which can improve the integration of performance of the structures with the design.

b. Need for standards that govern sensor calibration and documentation of stochastic information regarding the measurement of certain environmental parameters.

c. Need for standards which would be valid in case of retrofitting structures to make sure that the retrofitting achieve its goal of strengthening the structure.

[4], [5] question whether only one damage-sensitive feature or a vector of various features is suitable for practical SHM systems. The author refer to the various causes of the damage and the inherent non stationarity of those causes suggest that both local and global approaches to SHM must be investigated simultaneously [6]–[9]. According to [10], the engineering structural health concept encompasses four distinct subsets:

a. Sensor allocation and measurements,
b. Structural identification,
c. Damage or degradation detection, and
d. Decision-making.

Damage identification methods can also be classified as “model-based method” or “response-based method”[11].

The model-based method assumes that a detailed numerical model of the structure is available for damage identification; while the response-based method depends only on experimental response data from structures[12], [13]. According to [9] the various considerations which influence the choice and effectiveness of SHM methods are:-

a. What is the level of damage and deterioration related to it,
b. The types of sensors used,
c. The degree of measurement noise pollution, and
d. The level of prior information about the condition of the structure, etc.

Structures are generally rated and monitored once a year or once in several years according to the importance and the age of the structure

Table 1previous studies in SHM

Authors	Findings
[14]	proposed a novel health indicator extraction method based on the available sensor parameters for the health monitoring of Air Conditioning System (ACS) of a legacy commercial aircraft model
[15]	Monitoring the parameters including temperature, humidity, pH, corrosion rate, and stress/strain and the sensors particularly fabricated based on fiber optic, Bragg grating, piezoelectric, electrochemical, wireless and self-sensing technologies.
[7]	The effect of varying environment needs to be considered and eliminated while conducting structural health monitoring.
[3]	It provides useful tools for processing and analyzing these big machinery data
[16]	“Describing the design, suggesting improvements in the V-notch sensors, evaluating stresses to predict the failure of critical components (such as bridge ways) by using ANSYS simulations to estimate the stresses through V-notch geometry passive sensors with different depths in the structure”.
[8]	Due to the complex behavior of mooring lines, a new design of Radial Basis Function (RBF) neural network is proposed for damage diagnosis.
[17]	The authors presents an original approach to structural health monitoring of helicopter rotors based on strain measurement on the blades

[12]	This paper deals with assessing the integrity of composite structures via modal acoustic emission (MAE) technique.
[13]	Non-destructive testing (NDT) techniques play an important monitoring (SHM) of composite structures, among which infrared thermography (IRT).
[9]	A novel framework to fuse structural health monitoring (SHM) data from different in-situ monitoring techniques is proposed aiming to develop a hyper-feature towards more effective prognostics.
[18]	The authors discussed the review of structures with structural health monitoring system.
[4]	presents a system that monitors the health of structural elements in Reinforced Concrete

7 Discussion

NDE techniques, which are commonly used for localized evaluation of large structures, fails when used for complete evaluation of the global and local performance of the structure. To examine the changes in the static and/or dynamic characteristics of the structure while monitoring their dynamic and/or static responses gives rise to the need of the development of the additional global damage detection methods which can be applied to the complex structures as well. The response-based techniques have the potential to evaluate the whole structure due to its simple setup and potential automation of data acquisition, data processing, and defect detection, [5], [10], [18]. Performance of the structures are determined by various factors such as the age of the building, material used, service condition and layout of the structure besides performance, safety, reliability and serviceability are also the crucial points. SHM technology is implemented in various countries like Europe, USA, Korea, Japan etc. for monitoring of large structures [4], [5], [7], [10], [13], [16]–[18] [19]–[21]. The main aim behind the implementation of SHM is to determine the damage during initiation itself so that the further damage propagation can be ceased by an alarm in the initial stage with the help of continuous monitoring by structurally integrated sensors.

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Assessment of the failure process of self-compacting concrete modified with SiO_2 nanoparticles by acoustic emission method

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Abstract

One of the new directions in self-compacting concrete (SCC) research is the modification of its composition with the addition of nanoparticles, which due to their unique properties are believed to improve the mechanical properties of cementitious composites. An important issue concerning the mechanical behavior of concrete under compression load is the failure process. At the moment, however, there is no knowledge of the effect of nanoparticles on the failure process of compressed SCC. The aim of the work is to investigate the failure process of compressed self-compacting concrete based on coarse and fine granite aggregate made both without and with SiO_2 nanoparticles in the amount of 2.0% and 4.0% of the cement weight. The research includes the determination of the levels of the initial cracking stresses σ_i and the critical stresses σ_{cr} that delimit individual stages of the studied process. Investigations were carried out using the acoustic emission (AE) method, and during the tests the recorded descriptors were the sum of counts (N_c) and the average effective value of the acoustic emission signal (RMS). The paper shows that the addition of SiO_2 nanoparticles has a positive effect on the failure process of compressed SCC. Moreover, the practical aspect of the obtained results for engineering purposes is provided.

Keywords: acoustic emission; failure process; initiate cracking and critical stresses; nanoparticles; self-compacting concrete.

1. Introduction

Self-compacting concrete (SCC) is widely used in the construction industry. Its uniqueness is confirmed by a number of advantages, including: the ability to compact itself under its self-weight, the possibility to execute structures with a high degree of reinforcement and with complex shapes, good adhesion to old concrete, and also the ability to obtain elements with smooth surfaces that lack of cracks [1]. This concrete has been used in building practice for about 35 years. However, there are continuous works carried out to improve this material. They involve the improvement of its composition with the use of additives with finer and smaller grains, including nanoparticles [2].

Nanoparticles are a very fine material with grains not exceeding 100 nm [3]. The obtaining of such small grains has become possible due to the development of building material engineering and the achievements of nanotechnology. The improvement of the composition of concrete with the use of components with an increasingly smaller grain size (Fig. 1) is seen to be positively influencing the structure of this structural material [4].

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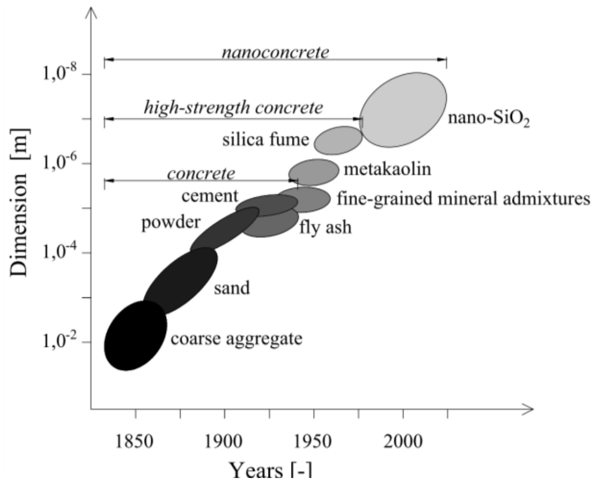

Fig. 1. The reduction in the grain size of components used to make concrete over time [4].

The following compounds are considered as a potential additive for the production of concrete: SiO_2, Al_2O_3, CuO, TiO_2, ZnO_2, Fe_2O_3 and Cr_2O_3 [5]. Nanoparticles that form nuclei around which products of the cement hydration process grow, as a result of high chemical reactivity, effectively reduce not desired calcium hydroxide and create additional amounts of the C-S-H phase in the concrete structure, while at the same time acting as a nano-filler of the concrete microstructure [6]. Thus, they increase the corrosion resistance of concrete [9] and improve its physical properties by reducing, among other things, porosity [7] and permeability [8]. At the same time, nanoparticles have a positive effect on the mechanical parameters of concrete, such as its compressive and bending strength [11], and they also increase its hardness, which is evaluated at the micro scale level [10]. Despite the advantages of modifying cement composites with nanoparticles, investigations concerning the failure process of concrete with the addition of nanoparticles are very selective [12-14]. It is worth emphasizing that knowledge of this process, mainly due to the influence of compressive loading, is an important and significant issue regarding the durability and safety of using building structures made of concrete [15].

The problem of the failure process of compressed concrete includes the formation, development, accumulation and propagation of micro-damage of a concrete structure under load. It has been proved that this process consists of three stages that are distinguished by the levels of stresses that initiate cracking σ_i and critical stresses σ_{cr} [16]. These levels are understood as certain contractual stress levels in loaded concrete, which delimit the qualitative changes that take place in the structure of concrete as a result of increasing loads. They are measures of the condition of constructions made of concrete, which allow changes that occur in it to be tracked. These levels are also considered as important strength characteristics of concrete, which describe its predisposition to signalled or not signalled cracking under the influence of the acting load [15]. It has been shown on the basis of research that the course of the failure process of compressed concrete is affected by a number of technological factors, including, among others, an additive that was used to make the concrete [15]. The effect of the addition of nanoparticles on the formation of levels of stresses that initiate cracking and critical stresses in SCC is interesting and necessary to investigate. This is especially due to the fact that these levels are correlated with the appropriate fatigue strength and long-term durability of concrete [17]. The knowledge acquired during scientific research would fill the existing gaps in literature concerning this subject.

The acoustic emission (AE) method is a method that enables continuous monitoring of the failure process of loaded concrete [15,18]. This method uses the phenomenon of creation and propagation of elastic waves in a material, which arise due to the release of the elastic energy that has accumulated in it. In the process of concrete failure, the source of the AE are the emerging and spreading micro-cracks, which occur as a result of the compressive load. When reaching a surface, the micro-cracks are received by acoustic emission transducers that convert them into electrical voltage. Finally, the signals, after being registered and digitally processed in the measuring apparatus, obtain the form of AE descriptors, such as, among others, the rate of AE counts, the sum of AE counts (N_c), and the average effective value of the AE signal (RMS).

Considering the above, the aim of the study is to learn about the process of failure of self-compacting concrete that is modified with SiO_2 nanoparticles using the acoustic emission method.

2. Description of tests

The following components were used to make mixes of self-compacting concrete for testing: Portland cement CEM I 52.5 R, which meets the requirements of EN 197-1 [19] and has a composition shown in Table 1; superplasticizer (SP) Glenium Sky 600 that is applied in an amount of 4.0% of the cement weight; tap water; and also granite aggregates with fractions of 10-5, 5-2, 2-1, 1.2-0.5, and 0.6-0.1 mm, as well as a fraction that has a grain size <0.1 mm and that acts as a small filler. Fine aggregate with a fraction of up to 2 mm accounted for 48% of the total aggregate. The W/C ratio of the designed concrete mixes was equal to 0.42.

Table 1. Chemical composition of the cement that was used in the tests.

Component	Content in the composition *(%)*
Cao	65.00
SiO_2	22.00
Al_2O_3	5.40
Fe_2O_3	3.30
MgO	3.20
Cl^-	< 0.08
Loss of roasting	3.0

The composition of the concrete mix was modified with SiO_2 nanoparticles in the form of a powder with a particle size of 10-20 nm (Fig. 2). Nanoparticles were used in an amount of 2.0% and 4.0% of the cement weight.

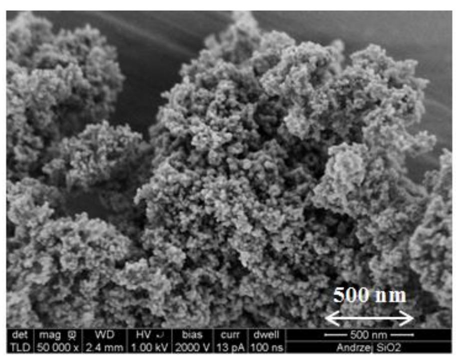

Fig. 2. SEM image of the SiO_2 nanoparticles that were used in the tests.

From the above-mentioned components, three mixes of self-compacting concrete were designed and made. One mix was prepared without the addition of nanoparticles and used as the reference one. The composition of all the designed mixes, calculated per 1 m^3, is shown in Table 2.

Table 2. Compositions of the designed mixes of self-compacting concrete calculated per 1m^3.

Mix	Cement (*kg*)	Aggregate (*kg*)	Water (*kg*)	Nanoparticles (*kg*)	SP (*kg*)
S1	460.0	1640.0	193.2	-	18.4
S2 (2.0% SiO_2)	450.8	1640.0	193.2	9.2	18.4
S3 (4.0% SiO_2)	441.6	1640.0	193.2	18.4	18.4

From each mix, with the designation and composition given in Table 2, a series of 6 cube specimens with dimensions of 100 x 100 x 100 mm were made. The specimens matured in a climatic chamber at an air temperature of 20 °C (± 1 °C) and relative humidity of 95% (± 5%). These series were designated in the same way as mixes S1, S2 and S3. After one year, from the previously prepared cubes, 6 specimens with dimensions of 50 x 50 x 100 mm were made for the tests using the acoustic emission method.

Tests using the acoustic emission method were carried out with the use of the Vallen-Systeme Gmbh AMS3 apparatus set, two VS 150-M sensors with a 100-450 kHz transmission band, and a hydraulic press. During compression of the specimens, the recorded acoustic emission descriptor as a function of time was the effective value of the RMS signal. The compression of the specimens was conducted with the elimination of friction at the interface of their surfaces with the pressure plates of the testing machine. For this purpose, the surfaces of the specimens were grinded until they were mutually parallel with an accuracy of 0.05 mm. They were then covered with a thin layer of technical grease. Figure 3 shows the view of the test stand for measuring the acoustic emission.

Fig. 3. The stand for testing the failure process using the acoustic emission method.

3. Research results and their analysis

Figures 4, 5 and 6 show the results of the course of the effective sound signal (RMS) of the acoustic emission. They were recorded as a function of time of the compressed tested concretes for the S1, S2 and S3 series. The diagrams also show an increase in the relative value of compressive stresses σ_c/f_c as a function of time of the compressed specimens, as well as the average levels of stresses that initiate cracking σ_{im} and critical stresses σ_{crm}.

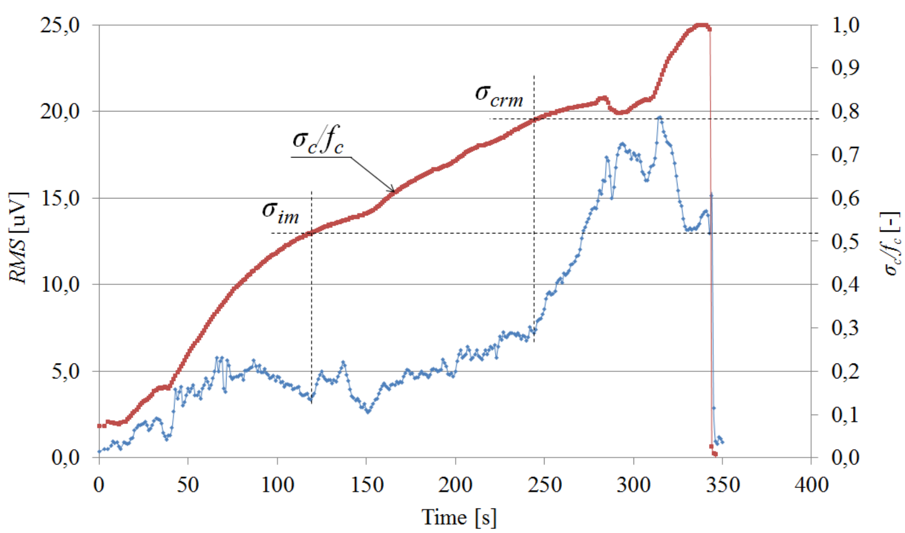

Fig. 4. The course of the effective value of the (RMS) acoustic emission signal with a diagram of the increase in the relative value of the compressive stresses σ_c/f_c as a function of time of the failure of the self-compacting concrete of series S1.

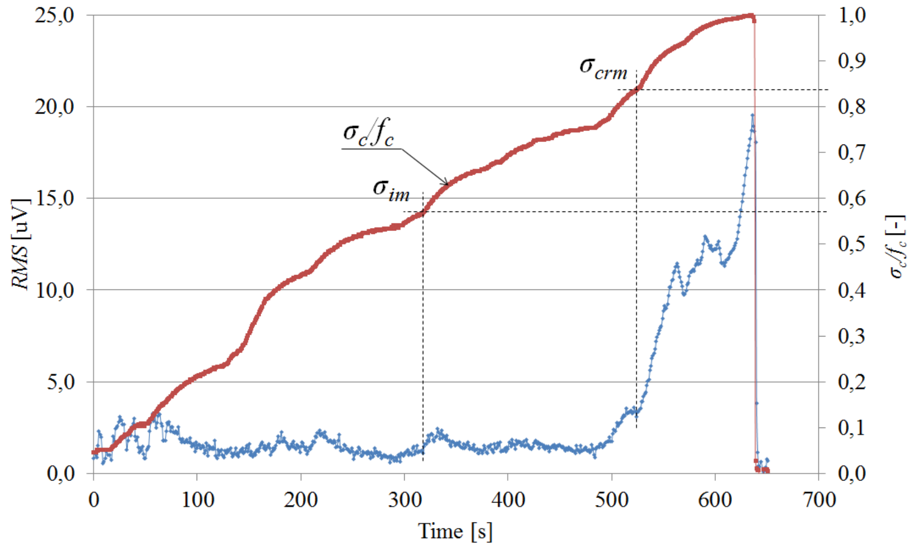

Fig. 5. The course of the effective value of the (RMS) acoustic emission signal with a diagram of the increase in the relative value of the compressive stresses σ_c/f_c as a function of time of the failure of the self-compacting concrete of series S2.

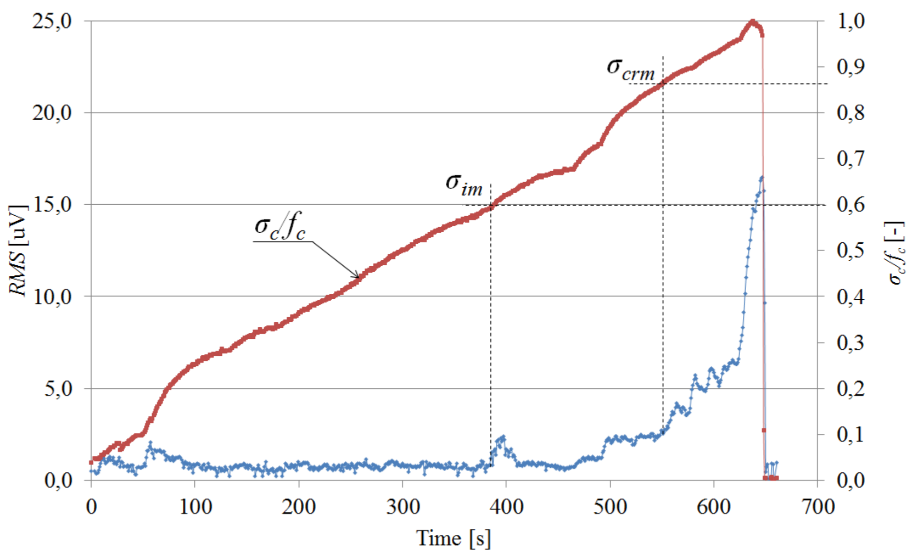

Fig. 6. The course of the effective value of the (RMS) acoustic emission signal with a diagram of the increase in the relative value of the compressive stresses σ_c/f_c as a function of time of the failure of the self-compacting concrete of series S3.

The presented test results confirm the three-stage process of the failure of all the tested concretes. On the course of the effective value of the acoustic emission signal (RMS), two thresholds between different stages are distinguished. The first, and less obvious, corresponds to the level of stresses that initiate cracking σ_i, and the second one, which is very distinct, corresponds to the level of critical stresses σ_{cr}. The obtained levels of these stresses are different depending on the tested series, and are summarized in Table 3.

Table 3. Results of average levels of stresses that initiate cracking σ_{im} and critical stresses σ_{crm} of the tested concrete.

Concrete series	σ_{im}/f_c (-)	σ_{crm}/f_c (-)
S1	0.52	0.78
S2 (2.0% SiO_2)	0.58	0.83
S3 (4.0% SiO_2)	0.60	0.86

In the case of the concrete with the addition of 2.0% of SiO_2 nanoparticles (S2), the obtained average levels of stresses that initiate cracking σ_i and critical stresses σ_{cr} are higher when compared to the reference series S1, which was without the addition of nanoparticles. It should be noted, however, that it is difficult to precisely determine the level of stresses that initiate cracking σ_i in the case of series S2. However, it can be assumed that it is higher when compared to the concrete series S1 after obtaining the result for the concrete with the addition of 4.0% of SiO_2 nanoparticles (S3). It is worth noting that the addition of 4.0% of SiO_2 nanoparticles results in a significant increase in the average levels of stresses that initiate cracking σ_i and critical stresses σ_{cr} in concrete in relation to series S1 and S2. It is a simultaneous effect of improving the compressive strength and porosity of concrete due to the addition of nano-sized particles, which was confirmed on the basis of the same concrete tests in study [20]. When considering the relationship between stresses that initiate cracking σ_i and fatigue strength, the obtained results indicate that concrete made with the addition of SiO_2 nanoparticles will be characterized by higher fatigue strength than the reference concrete.

4. Summary

The paper presents the results of tests of self-compacting concrete with the addition of SiO_2 nanoparticles using the acoustic emission method. The three-stage process of destruction of this concrete was confirmed. It was found that the addition of SiO_2 nanoparticles causes an increase in the level of stresses that initiate cracking σ_i and critical stresses σ_{cr}, which may be related to the improvement of other physical and mechanical properties of the tested concrete. Considering the fact that the level of stresses that initiate cracking σ_i is seen to be equal to the fatigue strength of concrete, it can be concluded that the durability and safety of structures subjected to repeatedly variable loads, such as girders, bridge plates or gantry beams made of concrete with the addition of SiO_2 nanoparticles, will be higher when compared to structures made of concrete without this additive.

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Biomimicry interventions for addressing global environmental challenges

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Abstract

Many damages have been done globally to the natural environment, all in a bid to providing essential amenities and addressing the infrastructural deficit. These actions have resulted in increased carbon footprint, excessive heat, loss of biodiversity, increase in pollutant level in the atmosphere, and fluctuating weather conditions among many others. One of the latest sustainability drives that aim to address the environmental challenges facing the world today is biomimicry. As a new field that seeks to study, extract and emulate the fantastic processes and mechanisms operational in nature, biomimicry has become the most accessible and available source of productive ideas and solutions to the global environmental issues. Currently, there have been records of sustainable and innovative technologies inspired by nature that provides solutions to these problems. This paper aims to create awareness around the selected few of the biomimetic solutions that address the diverse environmental challenges facing humanity with a focus on energy and water issues. Been aware of the existence of these nature-inspired innovative technologies and solutions and their mode of operation is believed will be a giant step in encouraging their adoption and implementation.

Keywords: assessment tools; built environment; construction materials; green building; sustainability.;

1. Introduction

The challenges facing the world today are manifesting themselves in the economic, political and environmental dimensions. The study of [1] describes global challenges as issues, factors or circumstances which has a significant potential for threatening global stability. As highlighted by [2], issues such as terrorism, global warming, natural disasters, nuclear weapon proliferation, diseases outbreak, migration, population growth, political instabilities and continuous thinning of the ozone shield are few of the numerous challenges. Other global issues include depleting clean air and water, climate change, energy supply, geopolitical conflicts, depleting natural resources, financial upheavals and food crisis [3]. The 2013 report by the World Economic Forum (WEF) also identified rising greenhouse gas (GHG) emissions, water supply crises, severe income disparity, chronic fiscal imbalances and mismanagement of an ageing population as the top five global risks to manifest over the next ten years [1]. As suggested by [4], how we can encourage a change in human behaviour, influence political will, and advance science and technology are questions to be posted in other to address these global challenges. However, environmental issues remain dominant among the numerous challenges facing the world, with the impacts cutting across all human sectors. Hence, the introduction of

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sustainable development (SD) or sustainability concepts as a means of combating and mitigating the numerous environmental issues facing humanity. In recognition of the need to address global challenges, the general assembly of the United Nations (UN) in 2015 adopted the 2030 agenda for SD which comprises of seventeen (17) sustainable development goals (SDGs) as presented in Table 1. The new agenda which reached its fourth year of implementation this year 2019 emphasises a comprehensive strategy to achieving SD for everyone as against the millennium development goals (MDGs) which lapsed in the year 2015.

Table 1. Sustainable development goals [5].

Goal	Description	
Goal 1	No Poverty	End poverty in all its forms everywhere
Goal 2	Zero Hunger	End hunger, achieve food security and improved nutrition and promote sustainable agriculture
Goal 3	Good Health and Well-Being	Ensure healthy lives and promote well-being for all at all ages
Goal 4	Quality Education	Ensure inclusive and equitable quality education and promote lifelong learning opportunities for all
Goal 5	Gender Equality	Achieve gender equality and empower all women and girls
Goal 6	Clean Water and Sanitation	Ensure availability and sustainable management of water and sanitation for all
Goal 7	Affordable and Clean Energy	Ensure access to affordable, reliable, sustainable and modern energy for all
Goal 8	Decent Work and Economic Growth	Promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all
Goal 9	Industry, Innovation and Infrastructure	Build resilient infrastructure, promote inclusive and sustainable industrialisation and foster innovation
Goal 10	Reduced Inequality	Reduce inequality within and among countries
Goal 11	Sustainable Cities and Communities	Make cities and human settlements inclusive, safe, resilient and sustainable
Goal 12	Responsible Consumption and Production	Ensure sustainable consumption and production patterns
Goal 13	Climate Action	Take urgent action to combat climate change and its impacts
Goal 14	Life Below Water	Conserve and sustainably use the oceans, seas and marine resources for sustainable development
Goal 15	Life on Land	Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss
Goal 16	Peace and Justice Strong Institutions	Promote peaceful and inclusive societies for sustainable development, provide access to justice for all and build effective, accountable and inclusive institutions at all levels
Goal 17	Partnerships to Achieve the Goal	Strengthen the means of implementation and revitalise the global partnership for sustainable development

Sustainability and SD are often seen as two confusing terminologies describing with different meanings. The term SD was captured in the 1987 report of the Brundtland Commission giving the most commonly-cited definition [6]. The commission defined SD as development that meets the needs of the present without compromising the ability of future generations to meet their own needs. SD is closely associated with supporting, ensuring and promoting a healthy human and natural environment [7]. Sustainability, on the other hand, means the use of natural resources in such a condition of equilibrium that they do not reach decay, depletion and an unrenewable point and can be handed down to the future generations [8]. Regardless of the definitions of sustainability and SD, we can infer that both have the potential to address global environmental issues effectively. In the pursuit and paradigm shift of the human environment towards sustainability, several concepts have been developed. As identified by [9], few of the sustainability concepts include the Natural Step, cradle to cradle, cradle to grave, lean construction, lean manufacturing, biomimicry, ecological economics, Factor 4 and Factor 10, ecological rucksack, biophilia, eco-efficiency, and ecological footprint among others.

As a relatively new field, biomimicry has become prominent among the sustainability concepts with a strong potential to solve human challenges in a sustainable manner. Biomimicry operates by identifying, studying, emulating and integrating ideas from nature to solve different problems facing humanity [10]. As described by [11], biomimicry is the quest of stakeholders and professionals in exploring nature's ingenuity (self-sustaining ecosystems, photosynthesis, natural medicines, self-assembly, self-cleaning) and then emulating these designs and processes to solve human problems. Hence, this paper presents biomimicry technologies (commercialised, developed and in the development stage) that address energy and water issues which are notable among the global environmental challenges. The paper presents a review of related literature on nature-inspired methodologies and solutions. The final section of the paper showcases and presents an evaluation of the biomimetic solutions identified, draws conclusions and proffer recommendations.

2. Historical background and overview of biomimicry

Historically, early humans relied solely on the natural world for survival and sustenance. There is a high dependency on nature for the provision of food, shelter, agricultural tools, weapons and hunting tools, medicine and pharmaceutical needs among others. Also, around 500 B.C, Greek philosophers perceive and consult the natural world for ideas that are harmonious and aesthetically pleasing [12]. Leonardo da Vinci's flying machines is a notable example of early scientist's and designer's practice of drawing inspiration from nature [13]. By mere observation and in-depth examination of nature, early scientists and innovators amass vital information and ideas about functionality, efficiency and effective resource utilisation. The interrelation between the forms, functions and ecosystems of natural organisms revealed a robust system and presented a rich source of sustainable inspiration for application in different sectors and fields. As informed by [14], the natural environment adheres to a remarkable morphological principle in generating interfaces rather than shields in enabling most favourable passage of matter. As affirmed by [15], strategies in nature can inspire solutions to human challenges.

Nature has been able to adapt and evolve to the varying conditions on earth through its over 3.8 billion years of evolution [11,16]. By meeting its own needs and solving its challenges, the natural world sustains itself thereby offering a knowledge deposit of innovative ideas and solutions to the numerous challenges the human environment is grappling with daily. Biomimicry, therefore, seeks to study and emulate the designs and processes in nature to solve human challenges in a sustainable manner. The term 'biomimicry' first appeared in the year 1982 as part of Connie L. Merrill's doctoral thesis. The thesis is titled "Biomimicry of the Dioxygen Active Site in the Copper Proteins Hemocyanin and Cytochrome Oxidase" [17]. A careful perusal of the thesis, however, reveals no connection to nature nor draws inspiration from the operations in the natural world. Biomimicry then became popularised in the year 1997 through the book authored by Janine M. Benyus, a biologist, and co-founder of Biomimicry Guild. The book titled "Biomimicry: Innovation Inspired by Nature" projected Benyus as the founder of this new field of study.

The practice of learning and drawing inspiration from nature for innovative solutions has seen the birth of multiple terms such as biomimesis, bioanalogous design, bionics, biognosis, bio-inspired design, biomimetics, bioinspiration, biodesign, and biorobotics among others [16,18,19]. The field or sector determine the term to employ for its application. For example, drawing inspiration from nature for application in the field of robotics will result in the use of the term biorobotics. Since this study focuses on biomimicry, the study of [20] affirm that there is no difference between 'biomimetics' and 'biomimicry'. Considering the sound of the terminology, biomimicry is perceived to be some branch of biological science. The biological and scientific affiliation to biomimicry only provides an avenue for studying and learning about the forms, processes and strategies in nature [21].

Literature has recorded several definitions of biomimicry since its research and application gained momentum in recent years. As defined by [22] and [23], biomimicry is the process of creating sustainable designs and solutions through the conscious study and emulation of natural forms, strategies, processes and ecosystems. Biomimicry heralds a paradigm shift from exploiting and extracting from nature to that which studies and learns from it. The application of biomimicry for birthing eco-friendly developments is gaining overwhelming significance. Notable among the breakthroughs recorded in the application of biomimicry spans through the field of medicine, robotics, engineering, environmental sciences, pharmaceuticals and security among numerous others. This paper, therefore, presents biomimicry applications for addressing the present-day global environmental challenges in other to provoke a conscious shift towards this new field of study with innumerable potentials.

3. Biomimicry solutions to global environmental challenges

Biomimicry has inspired environmental-friendly innovative breakthroughs in different sectors with remarkable physical, chemical and mechanical characteristics [24]. According to [25], other advantageous qualities these technologies posses include low weight and reduced manufacturing costs compared to the traditional ones. It is, therefore, imperative for all stakeholders to consult with nature in learning solutions for adapting, mitigating and reversing the various environmental challenges facing humanity today. Below are carefully selected biomimicry solutions out of the pool of many for addressing global environmental challenges as compiled by AskNature [26]. This paper addresses two major areas where biomimicry has been successful in innovating technologies that tackle global environmental challenges namely *biomimicry solutions for energy challenges* and *biomimicry solutions for water challenges*.

3.1. Biomimicry solutions for energy challenges

Energy security, rising energy costs and most especially the adverse environmental impacts of energy production, generation and distribution are necessitating the research, development and investments in renewable energy sources. However, the application of biomimicry has seen the development of clean and renewable energy as a way of addressing global environmental challenges emanating from energy-related issues. An example is the Solar Botanic energy harvesting trees which are artificial trees that convert wind energy and electromagnetic waves from the sun via its nanoleaf technology. Innovated by SolarBotanic Ltd and still at the development stage, this new bio-inspired solar/wind energy technology aims to energise the future by providing renewable, carbon-free and clean energy through the combination of wind and solar power. Through the photosynthetic cycle of their leaves, plants have been maximally harnessing the solar radiation received on the earth surface. Solar Botanic energy harvesting trees aims to emulate the same process of photosynthesis by using electromagnetic collectors (Nantennas), which are lower in costs and with improved efficiency (up to 92%) compared to conventional silicon-based solar cells. When commercialised, this technology has the potential for reducing energy costs per kWh, increasing output and improving return on investment (ROI) which are the significant challenges hindering renewable energy deployments.

Power Plastic solar cell technology innovated by Konarka Technologies Inc. is another example of biomimicry breakthroughs in energy solutions. Konarka Power Plastic thin film dye-sensitised solar cells is a photovoltaic material that captures and converts outdoor and indoor light to direct current (DC) electrical energy. This technology is inspired by the process where a continuous influx of photons generates a continuous flow of electrons along the electron transport chain in plants. The process of capturing and converting energy in plants informed a low-temperature, low-cost and high-speed method of developing flexible, plastic, nanocrystalline solar cells. The energy produced from this technology can be stored for later use, converted to other forms or immediately used with potential for application in broad range areas such as remote and portable power, buildings, sensing, computing, communications and lighting.

Another nature-inspired technology is the Dye Solar Cell Technology innovated by Dyesol, described as ‘artificial photosynthesis’ using an electrolyte, a layer of titania (a pigment used in white paints and toothpaste) and ruthenium dye sandwiched between glass. The light striking the dye excites electrons which are absorbed by the titania to become electric current multiple times stronger compared to that found in natural photosynthesis in plants. The manufacture of this technology is lower in cost and uses embodied energy. Dyesol’s solar cell technology produces more efficient electricity even in low light conditions compared to the traditional silicon-based photovoltaic technology.

Energy consumption in buildings and the CI as a whole is enormous. Energy use in cooling and heating buildings accounts for a significant percentage of the total energy consumed. RavenBrick smart walls and windows (thermally-tintable glass and thermally dynamic walls) by RavenBrick LLC is another bio-inspired innovation that addresses energy issues. It emulates the passive pigmentation and passive thermoregulation strategy found in natural organisms such as cephalopods and many lizard species. This technology maximises natural sunlight to save on lighting and improve the indoor quality for occupants by maintaining comfortable temperatures.

3.2. Biomimicry solutions for water challenges

Another major challenge facing the world are water-related in terms of provision and access to clean, affordable and safe water. Most of these challenges are notable among developing countries where there have been records of draught, water-borne diseases and epidemics (due to sick and unhealthy water sources and channels), and other water-related challenges. Biomimicry as a pool of sustainable ideas has propelled the innovation, development and commercialisation of technologies that address global environmental challenges that are water-related. Water filters innovated by Baleen Filters is a notable example of nature-inspired technologies that address water challenges. Baleen Filter's water filters are non-pressurised, efficient, self-cleaning water filtering system that filters and purifies water without the use of chemicals. Baleen Filter was inspired based on studies on whales and patented by the University of South Australia. Baleen as a filter mechanism enables filter-feeding whales to filter small fishes and other aquatic organisms during feeding. Combining the sweeping action of the tongue and the reversing water flows as the whale dives and re-surface during feeding enables them to capture and strain food, thereby cleaning their baleen against their next dive. The system is a greener path to water re-use and recycling.

Another bio-inspired solution that addresses water-related challenges is the BioHaven floating islands innovated by Floating Island International. This technology is inspired by how natural floating islands and natural wetlands filter sediments and nutrients out of surface water, generally emulating how a wetland ecosystem functions. BioHaven floating islands are created using non-toxic, durable post-consumer plastics and vegetated with native plants. This technology is useful for reducing total suspended solids and dissolved organic carbon in waterways and are perfectly fit for areas with fluctuating water levels due to their floating attributes.

Aquaporin membrane technology by Aquaporin is a water filtration and purification technology. This technology is inspired by Aquaporins who are selective membrane channel proteins found in the lipid bilayer of living cells that aid the transportation of water across the cell membrane while excluding any particles that are not water. Based on this process and strategy found in nature, Aquaporin can perfect the formulation of low-energy water filtration and purification technology which can be employed in industrial and household structures. This technology is also able to solve the inefficient and energy-intensive problems associated with the existing water filtration and purification techniques.

Green infrastructure stormwater control innovated by Numerous cities worldwide is a stormwater control and management system that is inspired by nature. In a natural ecosystem, the vegetation and soil therein provide a filtering mechanism through above-ground structures for water runoff. The above-ground structures slow down water runoff, allowing it to sink into the soil making sediments settle out as it moves through the vibrant soil ecosystem of fungi, bacteria, plant roots, and other organisms. Due to many hard surfaces and structures in our cities such as buildings, sidewalks, parking lots, and roads among others, stormwater is prevented from soaking into the ground as it would in a natural ecosystem of soils and plants. Also, water runoff due to rainstorm and stormwater overflow combines contaminants and pollutants such as pesticides, oil and grease, metals, plastics and many others that end up in surrounding waterways that serve as drinking water sources. With bio-inspired innovations like the green infrastructure stormwater control technology, concerns over the management of stormwater which have been around for years will be a thing of the past.

4. Conclusion and recommendations

Biomimicry seeks to study and infer the excellent methods, strategies, forms, and ecosystems in nature to proffer sustainable solutions to the problems facing the human world. Since it came to limelight and became popularised, biomimicry thinking has been integrated into virtually all sectors with incredible and amazing results. As an important and potent sustainability concept, biomimicry aims at achieving the social, environmental and economic dimensions holistically. Despite been a new field and concept, biomimicry has propelled the development of sustainable technologies and materials that are characterised and known to be efficient and effective. Biomimicry solutions for water-related challenges offer the opportunity for increased and efficient water re-use and recycling, wastewater treatment and handling, reclamation of land used for settling ponds, clean-up systems and emergency pollution response for oil spills and land remediation among others. A major advantage is the innovative and enhanced separation capability characteristics of biomimicry technologies aimed at tackling water-related issues. Biomimicry has seen the innovation of renewable sources of energy which is renowned for being the best alternative to the present and unsustainable way of power generation and distribution. Biomimicry smart windows possess variable tinting based on temperature. They can provide significant energy savings by reducing heating and cooling costs in differing weather conditions. Smart walls store thermal energy through phase-change materials which are to be released during periods of lower temperature. With the duo of smart walls and windows, building energy consumption will be drastically reduced. By embracing and adopting biomimicry in its entirety, several innovative and sustainable solutions are bound to be birthed in response to the numerous environmental challenges facing the world. It is, therefore, recommended that governments and international agencies richly fund research and development (R&D) in the field of biomimicry. By so doing, the discovery and successful development of more efficient and effective solutions and technologies that address each of the global environmental challenges.

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Creative construction and simplicity of form

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Abstract

An Architect designing a form has to take many factors into account. Some are mainly pragmatic and rational in nature. They correspond with the needs and restrictions determined by the user, site or function to name a few. Other factors are subjective to the designer, his/her talent and creativity.
One of many tendencies in contemporary architecture is designing buildings that look surprising and innovative. Their complex geometries are usually showing the prestige and the use of modern techniques and technologies.
In architecture the relationship between pragmatism, creativity, prestige and astonishment can be seen in buildings which are simple and solid blocks. The feeling of surprise is hidden in the internal structure. The outer form is designed in a pragmatic way while the interior form is different and stunning to the observer. This structure may serve a functional purpose, but the way it is composed into the whole is unexpected. It is this creative construction that underlines the importance and prestige of the object. The relationship between these two structures drives the innovative character of the design.
The skill of intuitively explaining a concept becomes essential in the early stage of creating a project, when an idea becomes explicit. A sketch depicting the design concept leading to the materialization of a building shows the architect's talent. The article examines case studies of objects built in recent years in Poland and in the world, in which such a relationship can be seen. The aim is to show the designers' motivation, the way of designing and realizing such buildings. This approach allows to outline, how creativity influences the design.

Peer-review under responsibility of the scientific committee of the Creative Construction Conference 2019.

Keywords: architectural design; building structure; creativity; surface curvature

1. The idea in architecture

The article discusses the simplicity of architectural form and creative construction solutions. Such solutions are associated with innovation in architecture and can be found in various forms. Usually, they are buildings whose form depart the principles of right – angle geometry. The attempt to define this phenomenon shows the intensification of expressionist tendencies, as well as the emergence of new possibilities in modern design technologies and techniques. Observing contemporary iconic experiments in architecture and focusing the research on spatial harmony, the article follows up Nina Juzwa's research on the origin of spatial form presented in Cracow, Poland in November 2018 [1]. It also aims at the appreciation of architectural beauty in the discussed cases.

Many interesting objects were built in Poland in the last years. Our goal is to show these architectural events in the context of global trends in public utility architecture. As it is necessary in such situations, the choice of examples is subjective.

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According to Vitruvius, a thought or an idea is the basis of an architectural design, but still is not architecture itself [2]. During the design process, the architect's idea is transformed by drawings and models. These are vital to the final execution of the concept. The form, beauty and functionality of a building is affected by a large group of people: architects, urban planners, developers, constructors, etc. Nowadays, mixed-use objects like city centres, malls, town districts, research facilities and cultural centres are built with increasing complexity. This in turn requires more and more complementary skilled specialists, changing architecture into a team endeavour. Furthermore, architecture can only exist when there's a need and business plan for it, "buildings are, after all, a business"[3].

Architecture is driven by pragmatic factors, like economics, complexity and the number of people needed to build an object. Despite its cultural significance, this makes architecture seemingly slightly less of an artistic undertaking than traditionally 'higher arts', such as painting, photography, or sculpture. Comfort and utility are the most important requirements of the facility user, so functional and technical conditions must be met. When they are fulfilled, the material quality, spatial form envisioned by the authors can contribute to the cultural dimension of an urban complex or building. In fashion, a distinction is made between everyday items (*cotidienne*) and rarely purchased, but trend-determining patterns (*haut couture*). Similarly, we can talk about architecture which, having the features of formal uncommonness, creates a new, surprising quality of the space. In literature there is a term Gesamtkunstwerk which describes a piece that is perfect both in its entirety and details. We use this term when talking about some amazing objects.

2. A discussion over architecture

During the international debate in the London Royal Academy organised by Charles Jencks in 1997, the term 'ecstatic' architecture was coined to reflect emotions and expressions in modern architecture. The term was inspired by the 17th century sculpture, *The Ecstasy of St. Theresa* by Lorenzo Bernini, that can be seen in Santa Maria della Vittoria church in Rome. It is the symbol of movement and dematerialisation of form in art. Nail Leach, an architect and theorist, points out the irony of this metaphor in which a sculpture, not a building created by one of the eminent Baroque designers, has been so enormously and timelessly appreciated. Dematerialisation of form and the impression of movement can also be found in architecture, for example in the early expressionism of modernism, as well as in many contemporary works. Current designs move toward litheness and transience of the form and to associations/relations with biotechnology and computer sciences. The debate concluded in the statement that the ecstatic form astonishes, almost shocks at the first encounter with architectural innovation [4].

In the age of social media and instant global communication, visibility of architectural objects directly influences their profitability. Tom Dyckhoff calls them *Wowhouses*, products of capitalism and its tendency to reward individualism and competition [3]. According to their initiators, prestigious objects trigger urban change. Also, architecture can be part of the institution branding strategy. Usually, the best known buildings stand out of their context; the viewer is surprised and intrigued before entering the building. Frank Gehry is well known for this approach, as the example of the flowing geometry of the Guggenheim Museum in Bilbao shows. Local regulations can put constrains on the architects' desire to surprise, which requires different solutions. This can be seen in two of his projects in Berlin, where the curvilinear geometry is hidden inside a box-shaped building. In the case of the DZ Bank headquarters, the uniqueness of a rectangular and elegant building is largely determined by its internal sculpture-like structure. The project of the concert hall Pierre – Boulez – Saal has an elliptical stage and seating area set inside a rectangular, historical building. The intent was to create an intimate space for musicians and listeners alike [5]. These examples do not repeat the traditionally expected patterns, instead they provide innovation. Similarly, the viewer's astonishment evoked by architectural ideas is also seen in case of the buildings by Japanese architects: the Rolex Learning Centre in Lausanne by Saana (2004) in which the smoothness of interior and the lack of zones are enhanced by the liquidity of the ceiling lines, or the building of the Media Library in Sandai, Japan by Toyo Ito & Associates. The building, in the form of a cuboidal glazed seven-storey-high box, has smooth transitions between floors. This impression is created by seaweed-like columns which allow visual connections between the levels [1].

3. Creative construction and simplicity of form – case studies in Poland

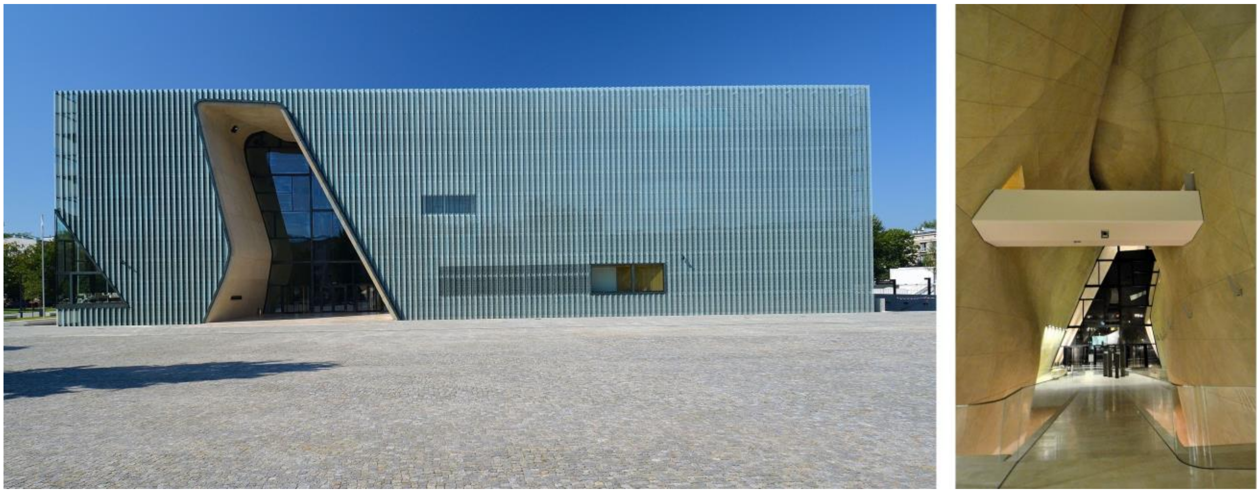

Fig. 1, Warsaw, the exterior and interior of the Museum of History of Polish Jews by Rainer Mahlamäki and Ilmari Lahdelma. Collage of photos by Adrian Grycuk, CC3, wikimedia commons

Form dematerialization frequently becomes the autonomic element of the very pragmatically shaped architectural structure of an object. A glimpse at the architecture of recent years reveals how special attention is paid to buildings which externally are solid, simple blocks, while their interiors are surprisingly innovative. The examples from Warsaw and Katowice are perfect illustration of this relationship.

Warsaw is a city of difficult and rich history more than often resulting in challenging urban and architectural situations. **The Museum of the History of Polish Jews – POLIN** designed by Rainer Mahlamäki and Ilmari Lahdelma (2013) is situated in Muranów, one of the districts of the city of Warsaw located in the close vicinity to the monument to the Warsaw Ghetto. The idea of the Museum is not only to commemorate the Holocaust. Its function is twofold – firstly, to teach how Jews contributed to the history of Poland, and secondly, to be a centre of culture and education. In 2005, Lahdelma & Mahlamäki from Finland won the contest for the building design.

From the outside, the building resembles a glass case full of Torah books. The panels creating the cover have the word POLIN written on them. The structure, designed pragmatically on a square floor plan, fully reveals its astonishing beauty only upon entering inside. The museum consists of 4 above-ground floors and 2 underground ones. Thanks to the geometrical simplicity and its height, it harmoniously blends into the surrounding of a post-war housing estate. It contains a hidden symbolism in the details of the architectural concept, which is aggressive neither to passers-by nor visitors.

The keystone of the interior space is a high entry hall. The whole architectural dramatism of the interior is hidden there. The building is torn in half across its dimensions to symbolize the history of Jews which may be interpreted in two ways: either as the crossing of the Red Sea or as the break of the history of Polish Jews during the Holocaust. Inside the building, it creates a high undulating passage layered with shotcrete. The gorge ends with the light which drips out of glass tiles enhancing the drama of the interior. The building, concise in form, creates sublime mood inside, which also enables the reflexion upon the passing of time. What makes the building memorable, is its simplicity and conciseness [1].

The city of Katowice is the capital of the former largest industrial region in Poland, currently in the period of economic and spatial transformation. Near the Silesian University and the famous Spodek (built in 1971), on the premises of a former coal mine a cultural zone was established. The goal of this huge investment is to enhance and complement the cultural offer of Katowice, as well as to change the image of the post-industrial city. Following a number of international architectural competitions, three objects were built: the seat of the Polish National Radio Symphony

Orchestra, the International Congress Centre and the Silesian Museum. The first two are perfect embodiments of the aforementioned design approach.

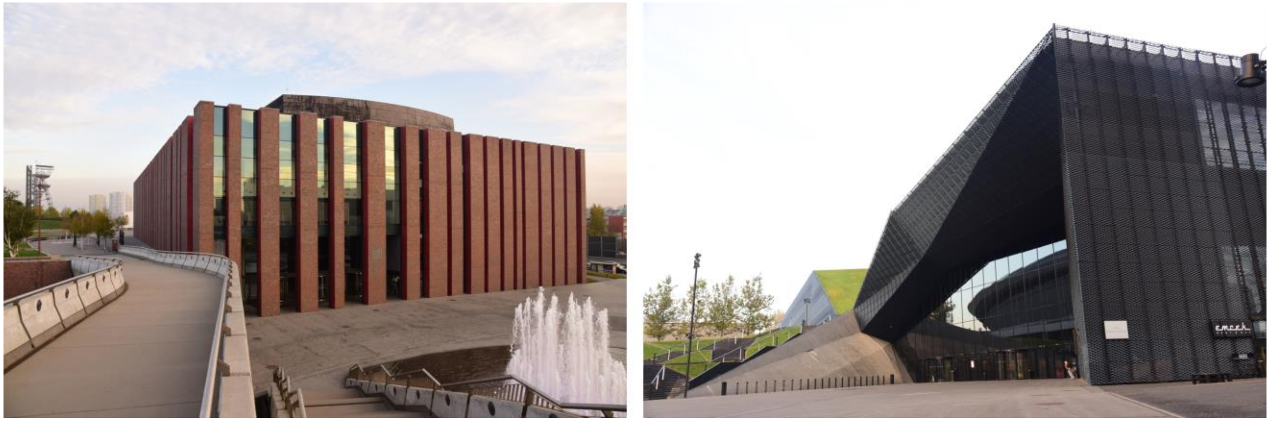

Fig. 2, Katowice, on the left the seat of the Polish National Radio Symphony Orchestra by Konior Studio, on the right the International Congress Centre by JEMS architects. Collage of photos by Dominika Zieleźnik (used with kind permission).

The seat of the **Polish National Radio Symphony Orchestra** was designed by Tomasz Konior in 2008. It is located on the former coal mine wood storage place. From the outside the building is a simple, regular block. With no references to classical architecture, the elevations consist of glass gaps and vertical brick pylons arranged in an irregular rhythm. The bricks are in different shades of red.

The building structure is based on a *box inside a box* logic, where the inner box contains the large concert hall. Even though this box is higher, it is only slightly visible from the outside, just hinting of its role. The concentric concept is seen in the floor plan, where the accompanying rooms are grouped along the outer walls, around the centrally located concert hall. In the outer ring, a second, smaller concert hall is located. From the white foyer one can enter the large concert hall. Looking from the hallway, the concert hall is an autonomous building element made of black concrete. The contrast between the smooth, white walls of the foyer and the dramatic and raw concert hall is, next to extraordinary acoustics, one of the key to the beauty of the building.

Both the small (seating 300 people) and the big (1 800 people) concert halls are finished in wood. The layout of the big concert hall resembles that of Hans Scharoun's Philharmonic Hall in Berlin. The scene is surrounded by the audience from all sides. Curved surfaces of the interior emphasize the oval drawing of the plan, creating the impression of sitting inside a musical instrument, fully immersed in the spectacle. The compact vineyard layout designed by the architect and acoustician (Nagata Acoustics) offers a great concert experience, both acoustic and visual [6].

The second building of Katowice cultural zone described in this article is the **International Congress Centre**, designed by the Polish architecture studio JEMS in 2008 and opened in 2015. The building is located next to the Spodek event hall, the icon of the city, and connected to it via a tunnel.

The Congress Centre serves many purposes like conferences, exhibitions, fairs and concerts. It looks like an enormous black box that has been cut through. The architects describe their design in the following way: "The rectangular structure is intersected by a *canyon* linking the entrance courtyard facing the Spodek arena with the historic route to the settlement of Bogucice. Cutting through a series of repeatable structural patterns, freely running public walkways are an idea which is also developed in our other landscape-scale designs […]" [7]. The characteristic *canyon* is a public space filled with green areas and offers surprising viewpoints that allow the observation of the surroundings. It also breaks visually the large scale of the 37 902 square meters object.

The green *canyon* has a complex geometry and contrasts with the black rectangular form of the Congress Centre. This form looks solid thanks to the elevations covered with a black metal net. The net is also used inside, where the canyon is visible in the form of a bent vault in the entrance hall. The dark finishing evokes feelings of being in underground corridors of a coal mine. The Architects have managed to achieve a difficult effect – the creation of a distinctive, surprising and original object that does not overwhelm the architectural icons in its vicinity and which fits in with the local traditions of 'black Silesia' [8].

4. The origin of architectural form

In his analysis of western architectural theories, Mark Gelernter distinguishes five main trends, five concepts making up the basis for organizing debates about architectural form, and these are as follows[1, 9]:

- Functional requirements shape the architectural form of the designed object. According to this idea, the form serves the needs of an investor/user. It is the result of analyses and explorations related to the project requirements, legislative constraints, and location requirements. Examples include stadiums and concert halls, where visibility and good acoustics are usually the basic differentiator for seeking formal solutions. Nevertheless, some objects differ in form, despite being built in a similar period of time and location.
- Creativity drives the design of the architectural form. The design which arises as a result of explorations is the effect of feelings and intuition of th architect. The historians of architecture have pointed that certain architects represent notably greater creativity and abilities of formal shaping.
- The Spirit of the Age as the main influence of the architectural forms. According to this concept it is not important how far the artistic creation of a designer goes. They share the ideas and opinions expressed by the society and environment they live and work in. No matter what the individual opinions of a designer are, he/she always depends on tendencies and images of architectural form. Mark Gelernter recalls the building of Bauhaus in Dessau (W. Gropius, 1926) and the palace of the viceroy in New Delhi, India (Sir E. Lutyens, 1911–1931), both created in the same period of time.
- Social and economic conditions as the main factor of shaping architectural form. Analogously to the Spirit of Age theory, local conditions determine architectural concepts, influence formal solutions and determine the actions of the architect. If, however, as in the above case, they come from a desire to change the traditional way of thinking and aim at introducing new formal solutions changing the existing paradigm, physically existing conditions restrain the creativity of the designer.
- Universal laws, beyond the creation of the architect and independent of the climate and geography determine the architectural form. This theory emphasises that some universal forms like basilicas, atria, courtyards, occurring in many solutions became the basis for architectural concepts, independently from culture. The design may undergo certain transformations, but the formal relation is significantly visible.

Mark Gelernter points out that none of the above mentioned theories can explain the origin of architectural form on its own. Looking closely at the analysed buildings, it is impossible to pin down the sole factor that determined such a design and thus it is advisable to look at the architects' opinion on their concepts:

- Mahlamäki creased the walls of the hall when he looked at the almost finished project that was a perfectly organized floor plan [1].
- Tomasz Konior based his idea on a box inside a box structure. Inside these boxes and in between them, different kinds of events can take place.
- JEMS Architects referenced the context of the location and the changing needs of the society transition from industrial to knowledge-based economies.

These designs introduced a regular, straight-angled geometry with a form that requires more advanced design and production technologies, additionally enhancing the prestige of the buildings.

In all those aspects the complex geometry is related to the creative approach of the architects. In order to classify the buildings according to Mark Gelernter, it seems that the architectural form of the Museum POLIN arouse from the architect's emotional need. In case of the Polish National Radio Symphony Orchestra, useful ideas from the past were developed, whereas the finesse of design solutions is the merit of the designer's knowledge and intuition. Similarly, the International Congress Centre design responds to the needs of modern society - that is, the architectural form of the building is the expression of the spirit of the age.

5. Conclusion

Hans – Georg Gadamer points at the importance of beauty, which in the assessment of art is the factor that operates independently of time, as well as social and political factors [10]. If we look at the architecture of the last few years, it becomes obvious that special attention is paid to buildings which seemingly are a compact, simple structures and this mystery of wonder - this architectural 'WOW' – is hidden in their interior structures.

Thought, matter and place are the three basic elements of architecture that can provide insight into life, human needs and dreams, and become a relay of communication between generations and between societies. We can experience our own legacy thanks to ancient buildings, situated in beautiful, important and sometimes inaccessible places, magnificent gothic cathedrals, medieval or renaissance piazzas with perfect proportions, and other wonderful buildings throughout history, as well as once destroyed or forgotten places that have been restored.

In the history of culture, the meaning of these places is not only the increasing perfection of technology and the evolution of architectural thought. It also means that the changing forms of human existence affect the change of human needs and perception of architectural beauty. In architecture, as in culture, the present means that buildings already created are engraved in our memory. This all-encompassing memory empowers us to create places with new architectural imagery.

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Framework of Project Delivery System Selection Tool based on Cross Functional Relationship

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Abstract

Construction project implements a typical project delivery method, procurement method, and contract types that have distinguished characteristics. Selecting the most sufficient method that has the benefits to success and reduces the risk of failure of the project has been a concerning point for project owners. This report is intended to suggest a framework of a project delivery system selection that considers the correlation between the project delivery method, procurement method, and contract types. The application of the tool for the owner will be in two steps. The first step to set up the initial goals and risks of the project to properly evaluate the tools and second step for answering the checklist questions based on the goals and risks that were set by themselves. As the characteristics of each type of delivery, procurement, or contract are defined from previous experience, our tool suggests the prior option of selection combination that can aid the owner's decision.

Keywords: Combined Project Delivery System; Project Delivery Method; Procurement Method; Contract Types

1. Introduction

The definition of project success is a topic that is keep being discussed in the academic and industry field, yet common definition of a project management success was defined with meeting the parameters of the iron triangle: Scope, Budget, and Schedule [1]. As various types of project delivery method, procurement method, and contract types appear for the project, it has become an owner's concern to find out a proper selection of the methods that suits their expectation. Previous studies have shown various methods such as the suggestion of decision supporting system using analytical hierarchy process by project characteristic [2], figuring out proper project delivery methods by empirical comparison between delivery types [3], and empirical analysis based on owner characteristics that affects project delivery types [4].

According to Project Management Institute (PMI), the success of a project is determined from either perspective of the project itself or what the project was intended to accomplish. Among the previous research in defining project success, the dominant stream aims to identify the factors that are likely to contribute to project success, failure, or risk [5] [6]

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[7]. With these contributing factors that have been considered decision support systems have been proposed for owners to decide that is sufficient for delivering the project efficiently [8]. Admittedly, the correlation between project delivery method and the contributing factors of project success is highly efficient but there wasn't enough study for selecting the proper delivery method within the restriction of procurement method or contract type. Which is why, this report suggests a tool for including the contributing correlation between the combination type in the project delivery system including; project delivery method, procurement method, and contract type.
The aim of this study is to develop a framework that could aid the owner in deciding various combinations of project delivery systems and show the influence that can be affected by a correlation between project delivery method, procurement method, and contract type. Which is why this study assuming the below limitation to demonstrate the logical flow of a combination of project delivery system more clearly.

- The choices to be assessed are the most common project delivery method (Design-Build, Design-Bid-Build, and Construction Manager at Risk), procurement method (Open Tender, Request for Proposal, Single-Source), and contract type (Fixed Rate, Fixed Price, Guaranteed Maximum Price).
- Critical success factors are interrelated with the type of projects [9], classification of success factors of the project was chosen for supporting owner's decision [10] [11] [12]; project schedule, budget and project complexity. As general factors of deciding project success have various views for the other factors than project schedule and budget. Project complexity is included for integrated factors such as quality, performance, and safety.

2. Overview

The process of implementing the benefit & risk relationship and cross-functional correlation selection tool is done in two phases. The first phase is divided into three steps which is (1) developing project goals and constraints, (2) gathering project checklist question results from the owner, (3) inputting the data into benefit & risk analysis. With analytical process of empirical data into a numerical value, an efficient rank of each method type will be decided for the project success. The second phase is divided into two steps which are (1) determining the most suitable project delivery system by each method type, and (2) review the result with considering the interdependent relationship between project delivery system components. Fundamental point for the adequacy of the data is the consistency of the owner's perspective for the project success. Therefore, determining project goals and constraints are the prior step of the data gathering. Once the project attributes are well defined, it is applied in terms of weightage of benefit & risk checklist measurement. The next step is gathering the checklist results and connecting the data with each benefit & risk of the alternatives. The checklist answers are transferred into an excel database to be linked as benefit or risk of three factors of project success; schedule, cost, and complexity. Most suitable project delivery components are decided by the matrix formulation of the relation between keywords of each option and benefits and risks of three factors of project success. In formulating the integrated matrix, an analysis was carried out using the Analytical Hierarchy Process (AHP) [13], are used to develop relative importance of the checklist questions. The flowchart shown in figure 1 illustrates how the two phases need to be facilitated. This will help in producing the best possible combination for project delivery system.

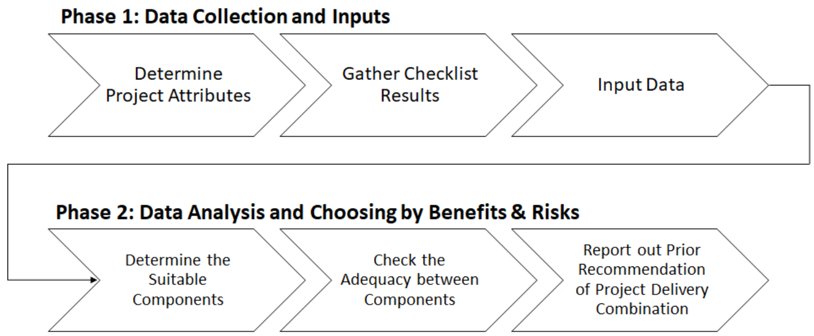

Fig. 1. Flowchart of the Project Delivery System Decision Process.

3. Phase 1: Data Collection and Inputs based on Benefit and Risks

3.1 Benefit and Risk analysis of each project delivery; procurement; contract types

The relationship between the questions on the checklist and the three factors (Project cost, project duration project complexity) are based on the benefits and the risk characteristics of each of the three project delivery systems (Project Delivery Methods, Procurement Method and Contract type). The relative importance of the checklist questions and three factors are influenced by the concept of Analytical Hierarchy Process (AHP). AHP is one of the various criteria decision supporting method. In this report highlights, the decision-making structure used with methods learned from AHP such as ranking and weighted score between the correlation of multiple criteria. At the top of this hierarchy, the goal of this checklist tool clearly defines 'Most Proper Combination of Project Delivery System for the Project'. After the checklist structure is established, the process of decision begins. The weightage of each checklist questions are directly derived from the owner's selection of priority of project goals & constraints. It will follow with each individual checklist question to be relating within the viewpoint of criteria and help in choosing the most preferable alternative delivery methods. Finally, the alternative delivery option method is ranked based on suitability to the project characteristics. In phase 2, further evaluation of cross-matrix checking of correlation of project delivery method-procurement method-contract type will be converted in a numerical scale to confirm the consistency of the combination.

3.2 Characteristic of Project Delivery Methods [14]

3.2.1 Construction Management at Risk (CMR)

In this system, owner contracts with an entity called Construction Management (CM) which could act solely as an agency or actively including itself with risk on the work. In each method, the CM may be brought on board early in the construction process, sometimes even before a designer is selected. Payment for CM services is generally done on a fixed fee basis, based on a percentage of the total construction cost [15].

3.2.2 Design-Bid-Build (DBB)

Design-Bid-Build is the traditional delivery type where the owner conducts a design competition with objectives to gain a designer for furnishing complete design services. Next, the owner will hold another bidding competition to gain a specific construction contract that is based on the designer's completed construction documents. In DBB, the owner "owns" the details of design during construction and, as a result, is financially liable for the cost of any design errors or omissions encountered during construction [16].

3.2.3 Design-Build (DB)

This is a project delivery method in which the owner procures design and construction services in the same contract from a single legal entity referred to as the design-builder. As the owner no longer owns the details of design, the owner's relationship with the design-builder must be based on a strong degree of mutual professional trust. The design-builder literally have full controls on the project in this project delivery method [16].

3.3 Characteristic of Procurement Methods

3.3.1 Open Tender

The main characteristics of an open tender are in clear and objective selections. Procurement with open tender method revolves in open competition between participants. The owner will publish basic requirements and specifications of the project locally or internationally. Based on that, all qualified participants need to prepare a bid while considering their own limitations and capabilities. The winning participant will be awarded to the least-cost provider. Thus, it is presumed as an effective competition that adds value for money. This method is highly preferred in public procurement projects as it deemed as the fairest and objective out of all methods [17].

3.3.2 Request for Proposal (RFP)

In RFP, participants are required to submit technical and financial proposals in two separate envelopes. The technical proposal is evaluated first and ranked according to pre-established evaluation criteria, and only the financial proposals of those firms that achieved the minimum qualifying mark (score), indicated in the RFP, are opened and evaluated [18].

3.3.3 Sole Source (Direct Select)

In Sole Source, the owner only appoints one partner without any kind of competition beforehand. Thus, this method hinges only on trust and relationship between owners and partners. However, some projects with this kind of arrangement are usually under pretext that there are no other trade parties with an equal amount of capabilities against the said partner [19].

3.4 Characteristic of Contract Types

3.4.1 Guaranteed Maximum Price (GMP)

In this contract, the work will be reimbursed on a time and materials basis to a fixed ceiling where the builder agrees to complete the work without additional payment once the ceiling is reached. Any cost overrun above that ceiling is a risk that the constructor takes, they would have to accept the payment as the lesser of the actual costs of the work plus a fee or the fixed ceiling amount [20].

3.4.2 Lump Sum (Fixed Price)

It is the traditional means of procuring construction, and still the most common form of a construction contract. Under a lump sum contract, a single 'lump sum' price for all the works is agreed before the works begin. Lump sum contracts apportion more risk to the contractor than other forms of contract, as there are fewer mechanisms that allow them to vary their price, and they need to give a client some guaranteed certainty about the likely cost of the projects. ("Lump sum contract - Designing Buildings" n.d.)

3.4.3 Fixed Rate

This contract is a type of contract based on estimated quantities of items and unit prices (rates: hourly rates, the rate per unit work volume, etc.). In general, the contractor's overhead and profit are included in the rate. The final price of the project is depending on the total quantities needed to carry out and complete the work. The Fixed Rate contract is only suitable for well-known resources involved project but unknown quantities at the time of the contract which will be defined when the design and engineering or construction work is completed.

3.5 Step 1: Filling in the Project Conditions

Project goals and constraints are evaluated from key factors of schedule, cost, and complexity of the project. Organizing and determining precise project attributes is the prior condition that needs to be consulted and understood for the owner to manage the project. The guide for the attributes and general conditions is elaborated as follows:
The project conditions are incorporated into the benefit & risk checklist as weightage of measurement. An owner should choose the fundamental project goals & constraints that can be recognized at the starting of the project. Weightage of each factor (schedule, cost, and complexity) of the project will be determined by the percentage of the items chosen for general goals and constraints from the owner. For example, if 3 items of schedule get chosen as general project goal & constraints when there are a total of 6 choices; 50% of weightage will be included when the schedule is counted for choosing suitable project delivery system. When more than one factor of schedule, cost, and complexity should be incorporated with benefit & risk checklist it would be used with the aggregation of the factors.

3.6 Step 2: Checklist of the Project Characteristics

A checklist will be processed based on the general project conditions chosen by the owner. Measurement will be based on the characteristic of benefits and risks for each factor depending on the items as per the given conditions & each individual answer from the checklists. The sample for a detailed checklist is shown in the table below. Ranking of each project delivery system, procurement method, contract type will be shown as the numeric result. Checklist questionnaire has been made with the following fundamentals:

- Questions that considers 'must' factor should be eliminated as this tool is for supporting general projects that are looking for the ideal point within meeting the iron triangle of project success
- Distribution of question relationship should not be biased into a single factor of schedule, cost, or complexity
- Correlation within questions should not be exact or opposite to avoid spillover effect of collecting duplicated data

Project Benefits & Risk Checklists				
No.	Questionnaire	Weightage	Checklist	
			Yes	No
1	Is it an intricate project?	0.667	V	
2	Are you financially constrained for this project?	0.333	V	
3	Is the project duration defined?	0.333	V	
4	Is the project familiar in the industry?	0.333	V	
5	Is the scope of project divided into separate unconnected phases?	0.333		V
6	Is advanced procurement beneficial to the project?	0.333		V
7	Is there a possibility of change in design?	1.000		V
8	Is there a possibility of change in scope?	1.000		V
9	Can the construction start before design completion?	0.667	V	
10	Is there an incentive for early completion?	0.333	V	
11	Is there a urgency to start the project?	0.333	V	
12	Is the penalty for late completion high?	0.333	V	
13	Are you willing to share risk & profit between all stakeholders?	0.667		V
14	Do you want to be strongly involved in the design phase?	0.333		V
15	Do you want to be strongly involved in the construction phase?	0.333		V
16	Are you able to make payments frequently?	0.333		V
17	Is cost more Important than quality?	0.333	V	
18	Is cost more important than project duration?	0.667	V	
19	Is there an incentive reducing project budget & duration?	0.667		V
20	Are you knowledgeable about the construction industry?	0.333		V
21	Does the Project allow high contingency reserve?	0.333		V

Fig. 2. Project Benefits and Risk Checklist

4. Phase 2: Analytical Hierarchy Process (AHP) for Correlation in Project Delivery Systems

In this phase, the correlation effect and suitability between each method in the project delivery system (project delivery methods, procurement methods, and contract type) are analyzed and implemented into the tool.

4.1 Step 1: Quality quantifying methods

Each checklist questions have been focused to be considered the same percentage of a criterion of project cost, duration, and complexity. Which is why 21 questions have been provided for 3 questions each for 6 types of correlation for 7 combination type of 3 criterions (cost, duration, and complexity). For the 21 checklist questions, questions produce a ‘dynamic recipe' with ‘Yes' or ‘No' value assigned for each alternative corresponding factor based on the benefit-risk evaluation made at phase 1. Questions having irrelevant properties and are assigned to ‘-/blank' on the factors. Thus, all the qualitative relations of benefits & risks are converted into quantitative numbers and ranks.

Subsequently, the user will answer the question with ‘Yes' or ‘No' and for every matched, it will be quantified as +1, unmatched will be -1, and ‘-/blank' will get 0. Calculated weightage from project conditions checklist in step 1 of phase-1 will be considered into quantifying the analysis, each question is assigned to the weightage corresponding the seven types of interaction it has on the three factors and possible combinations. The weightage is multiplied to the value of each cell which is then totaled and ranked. The analysis will create a rank of recommendation for the 3 alternatives between each parameter.

Project Benefits & Risk Checklists			Project Delivery Method									Procurement Method									Contract Type								
No.	Questionnaire	Weightage	DBB			DB			CMR			Open Tender			RFP			Direct Selected			Fixed Rate			Fixed Price			GMP		
			Cs	D	Co	Cs	D	Co	Cs	D	Co	Cs	D	Co	Cs	D	Co	Cs	D	Co	Cs	D	Co	Cs	D	Co	Cs	D	Co
1	Is it an intricate project?	1	N	-	Y	Y	-	Y	Y	-	N	-	-	N	-	-	Y	-	-	Y	-	-	Y	-	-	N	-	-	Y
2	Are you financially constrained for this project?	1	Y	-	-	N	-	-	N	-	-	Y	-	-	N	-	-	N	-	-	N	-	-	Y	-	-	Y	-	-
3	Is the project duration defined?	1	-	Y	-	-	Y	-	-	N	-	-	Y	-	-	Y	-	-	N	-	-	N	-	-	Y	-	-	Y	-
4	Is the project familiar in the industry?	1	-	-	Y	-	-	Y	-	-	N	-	-	Y	-	-	N	-	-	N	-	-	Y	-	-	N	-	-	N
5	Is the scope of project divided into separate unconnected phases?	1	-	-	-	-	Y	-	-	Y	-	-	-	-	-	Y	-	-	Y	-	-	Y	-	-	N	-	-	-	-
6	Is advanced procurement beneficial to the project?	1	-	N	-	-	Y	-	-	Y	-	-	N	-	-	N	-	-	Y	-	-	Y	-	-	N	-	-	Y	-
7	Is there a possibility of change in design?	1	N	-	N	Y	-	Y	N	-	N	Y	Y	-	Y	Y	-	N	N	-	Y	-	-	N	-	-	N	-	-
8	Is there a possibility of change in scope?	1	N	-	N	Y	-	Y	N	-	N	Y	Y	-	Y	Y	-	N	N	-	Y	-	-	N	-	-	N	-	-
9	Can the construction start before design completion?	1	-	N	N	-	Y	Y	-	Y	Y	-	N	N	-	N	N	-	Y	Y	-	Y	-	-	N	-	-	Y	-
10	Is there an incentive for early completion?	1	-	Y	-	-	N	-	-	N	-	-	Y	-	-	Y	-	-	N	-	-	N	-	-	Y	-	-	N	-
11	Is there a urgency to start the project?	1	-	N	-	-	Y	-	-	Y	-	-	N	-	-	N	-	-	Y	-	-	-	-	-	-	-	-	Y	-
12	Is the penalty for late completion high?	1	-	N	-	-	Y	-	-	N	-	-	Y	-	-	Y	-	-	N	-	-	N	-	-	Y	-	-	Y	-
13	Are you willing to share risk & profit between all stakeholders?	1	N	-	N	Y	-	Y	N	-	N	N	-	N	N	-	N	Y	-	Y	Y	-	-	N	-	-	N	-	-
14	Do you want to be strongly involved in the design phase?	1	-	-	Y	-	-	Y	-	-	N	-	-	N	-	-	Y	-	-	Y	-	-	-	-	-	-	-	-	-
15	Do you want to be strongly involved in the construction phase?	1	-	-	Y	-	-	Y	-	-	N	-	-	N	-	-	Y	-	-	Y	-	-	-	-	-	-	-	-	Y
16	Are you able to make payments frequently?	1	Y	-	-	N	-	-	Y	-	-	Y	-	-	Y	-	-	N	-	-	Y	-	-	N	-	-	Y	-	-
17	Is cost more Important than quality?	1	Y	-	-	N	-	-	N	-	-	Y	-	-	N	-	-	N	-	-	N	-	-	Y	-	-	N	-	-
18	Is cost more important than project duration?	1	Y	N	-	N	Y	-	N	Y	-	Y	N	-	Y	N	-	N	Y	-	N	Y	-	Y	N	-	N	Y	-
19	Is there an incentive reducing project budget & duration?	1	N	N	-	Y	Y	-	Y	Y	-	-	-	-	-	-	-	-	Y	-	N	N	-	Y	Y	-	N	N	-
20	Are you knowledgeable about the construction industry?	1	-	-	N	-	-	Y	-	-	N	-	-	Y	-	-	Y	-	-	N	-	-	-	-	-	-	-	-	-
21	Does the Project allow high contingency reserve?	1	N	-	-	Y	-	-	Y	-	-	N	-	-	N	-	-	Y	-	-	Y	-	-	N	-	-	N	-	-

Cs= Cost
D= Duration
Co= Complexity

Fig. 3. Relationship between Checklist questions and Project parameters

Cross-functional relationship process step will be automatically measured by the below steps;

1. Insert weightage of each question according to project constraints and goals selected,
2. Answering all the questions with a (✓) mark on “Yes” or “No”, attributed to the project condition,
3. Acquire the total result and ranks of alternatives of each method & type,
4. Check the interdependent relationship within the integrated matrix,
5. Find the best suitable combination for the project.

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Project Benefits & Risk Checklists			Checklist		Project Delivery Method									Procurement Method									Contract Type								
					DBB			DB			CMR			Open Tender			RFP			Direct Selected			Fixed Rate			Fixed Price			GMP		
No.	Questionnaire	Weightage	Yes	No	Cost	Duration	Complexity	Cost	Duration	Complexity	Cost	Duration	Complexity	Cost	Duration	Complexity	Cost	Duration	Complexity	Cost	Duration	Complexity	Cost	Duration	Complexity	Cost	Duration	Complexity	Cost	Duration	Complexity
1	Is it an intricate project?	0.667	V		-0.67	0.00	0.67	0.67	0.00	0.67	0.67	0.00	-0.67	0.00	0.00	-0.67	0.00	0.00	0.67	0.00	0.00	0.67	0.00	0.00	0.67	0.00	0.00	-0.67	0.00	0.00	0.67
2	Are you financially constrained for this project?	0.333	V		0.33	0.00	0.00	-0.33	0.00	0.00	-0.33	0.00	0.00	0.33	0.00	0.00	-0.33	0.00	0.00	-0.33	0.00	0.00	-0.33	0.00	0.00	0.33	0.00	0.00	0.33	0.00	0.00
3	Is the project duration defined?	0.333	V		0.00	0.33	0.00	0.00	0.33	0.00	0.00	-0.33	0.00	0.00	0.33	0.00	0.00	0.33	0.00	0.00	-0.33	0.00	0.00	-0.33	0.00	0.00	0.33	0.00	0.00	0.33	0.00
4	Is the project familiar in the industry?	0.333	V		0.00	0.00	0.33	0.00	0.00	0.33	0.00	0.00	-0.33	0.00	0.00	0.33	0.00	0.00	-0.33	0.00	0.00	-0.33	0.00	0.00	0.33	0.00	0.00	-0.33	0.00	0.00	-0.33
5	Is the scope of project divided into separate unconnected phases?	0.333		V	0.00	0.00	0.00	0.00	-0.33	0.00	0.00	-0.33	0.00	0.00	0.00	0.00	0.00	-0.33	0.00	0.00	-0.33	0.00	0.00	-0.33	0.00	0.00	0.33	0.00	0.00	0.00	0.00
6	Is advanced procurement beneficial to the project?	0.333		V	0.00	0.33	0.00	0.00	-0.33	0.00	0.00	-0.33	0.00	0.00	0.33	0.00	0.00	0.33	0.00	0.00	-0.33	0.00	0.00	-0.33	0.00	0.00	0.33	0.00	0.00	-0.33	0.00
7	Is there a possibility of change in design?	1.000		V	1.00	0.00	1.00	-1.00	0.00	-1.00	1.00	0.00	1.00	-1.00	-1.00	0.00	-1.00	-1.00	0.00	1.00	1.00	0.00	-1.00	0.00	0.00	1.00	0.00	0.00	1.00	0.00	0.00
8	Is there a possibility of change in scope?	1.000		V	1.00	0.00	1.00	-1.00	0.00	-1.00	1.00	0.00	1.00	-1.00	-1.00	0.00	-1.00	-1.00	0.00	1.00	1.00	0.00	-1.00	0.00	0.00	1.00	0.00	0.00	1.00	0.00	0.00
9	Can the construction start before design completion?	0.667	V		0.00	-0.67	-0.67	0.00	0.67	0.67	0.00	0.67	0.67	0.00	-0.67	-0.67	0.00	-0.67	-0.67	0.00	0.67	0.67	0.00	0.67	0.00	0.00	-0.67	0.00	0.00	0.67	0.00
10	Is there an incentive for early completion?	0.333	V		0.00	0.33	0.00	0.00	-0.33	0.00	0.00	-0.33	0.00	0.00	0.33	0.00	0.00	0.33	0.00	0.00	-0.33	0.00	0.00	-0.33	0.00	0.00	0.33	0.00	0.00	-0.33	0.00
11	Is there a urgency to start the project?	0.333	V		0.00	-0.33	0.00	0.00	0.33	0.00	0.00	0.33	0.00	0.00	-0.33	0.00	0.00	-0.33	0.00	0.00	0.33	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.33	0.00
12	Is the penalty for late completion high?	0.333	V		0.00	-0.33	0.00	0.00	0.33	0.00	0.00	-0.33	0.00	0.00	0.33	0.00	0.00	0.33	0.00	0.00	-0.33	0.00	0.00	-0.33	0.00	0.00	0.33	0.00	0.00	0.33	0.00
13	Are you willing to share risk & profit between all stakeholders?	0.667		V	0.67	0.00	0.67	-0.67	0.00	-0.67	0.67	0.00	0.67	0.67	0.00	0.67	0.67	0.00	0.67	-0.67	0.00	-0.67	-0.67	0.00	0.00	0.67	0.00	0.00	0.67	0.00	0.00
14	Do you want to be strongly involved in the design phase?	0.333		V	0.00	0.00	-0.33	0.00	0.00	-0.33	0.00	0.00	0.33	0.00	0.00	0.33	0.00	0.00	-0.33	0.00	0.00	-0.33	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
15	Do you want to be strongly involved in the construction phase?	0.333		V	0.00	0.00	-0.33	0.00	0.00	-0.33	0.00	0.00	0.33	0.00	0.00	0.33	0.00	0.00	-0.33	0.00	0.00	-0.33	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-0.33
16	Are you able to make payments frequently?	0.333		V	-0.33	0.00	0.00	0.33	0.00	0.00	-0.33	0.00	0.00	-0.33	0.00	0.00	-0.33	0.00	0.00	0.33	0.00	0.00	-0.33	0.00	0.00	0.33	0.00	0.00	-0.33	0.00	0.00
17	Is cost more Important than quality?	0.333	V		0.33	0.00	0.00	-0.33	0.00	0.00	-0.33	0.00	0.00	0.33	0.00	0.00	-0.33	0.00	0.00	-0.33	0.00	0.00	-0.33	0.00	0.00	0.33	0.00	0.00	-0.33	0.00	0.00
18	Is cost more important than project duration?	0.667	V		0.67	-0.67	0.00	-0.67	0.67	0.00	-0.67	0.67	0.00	0.67	-0.67	0.00	0.67	-0.67	0.00	-0.67	0.67	0.00	-0.67	0.67	0.00	0.67	-0.67	0.00	-0.67	0.67	0.00
19	Is there an incentive reducing project budget & duration?	0.667		V	0.67	0.67	0.00	-0.67	-0.67	0.00	-0.67	-0.67	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-0.67	0.00	0.67	0.67	0.00	-0.67	-0.67	0.00	0.67	0.67	0.00
20	Are you knowledgeable about the construction industry?	0.333		V	0.00	0.00	0.33	0.00	0.00	-0.33	0.00	0.00	0.33	0.00	0.00	-0.33	0.00	0.00	-0.33	0.00	0.00	0.33	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
21	Does the Project allow high contingency reserve?	0.333		V	0.33	0.00	0.00	-0.33	0.00	0.00	-0.33	0.00	0.00	0.33	0.00	0.00	0.33	0.00	0.00	-0.33	0.00	0.00	-0.33	0.00	0.00	0.33	0.00	0.00	0.33	0.00	0.00
					4.00	-0.33	2.67	-4.00	0.67	-2.00	0.67	-0.67	3.33	0.00	-2.33	0.00	-1.33	-2.67	-0.67	0.00	1.33	0.00	-4.00	0.33	1.00	4.00	-0.33	-1.00	2.67	2.33	0.00
		Total			6.33			-5.33			3.33			-2.33			-4.67			1.33			-2.67			2.67			5.00		
		Rank			1			3			2			2			3			1			3			2			1		

Fig. 4. Project Benefits and Risk Checklist

4.2 *Step 2: Decision with considering an interdependent relationship*

For this step, an analysis of interdependent relationships is implemented between all parameters. An important point to keep in mind is one specific alternative (e.g. in a parameter of project delivery system) might be unsuitable to other specific alternatives from other parameters (procurement method and contract type). Thus, an integrated matrix will be constructed to evaluate the best possible combination by evaluating compatibilities between these alternatives. The matrix is then compiled by ranks to give out the best possible combinations considering the type of relations.

	DBB	DB	CMR	Open Tender	RFP	Direct Selected	Fixed Rate	Fixed Price	GMP
DBB	-	-	-	1	-1	-1	1	1	-1
DB	-	-	-	-1	1	1	-1	1	1
CMR	-	-	-	1	1	-1	-1	-1	1
Open Tender	1	0	1	-	-	-	1	-1	1
RFP	1	1	0	-	-	-	1	-1	-1
Direct Selection	-1	1	-1	-	-	-	1	1	-1
Fixed Rate	1	0	-1	1	1	1	-	-	-
Fixed Price	1	1	-1	-1	-1	1	-	-	-
GMP	1	-1	1	1	-1	-1	-	-	-

Fig. 5. Interdependent Relationship Matrix

From the above reasoning, the process of interdependent relationship is as follows:

1. Select a method based on the highest quantified point acquired,

0.00	0.00	0.33	0.00	0.00	-0.33	0.00	0.00	0.33	0.00	0.00	-0.33	0.00	0.00	-0.33	0.00	0.00	0.33	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.33	0.00	0.00	-0.33	0.00	0.00	-0.33	0.00	0.00	0.33	0.00	0.00	0.33	0.00	0.00	-0.33	0.00	0.00	-0.33	0.00	0.00	0.33	0.00	0.00	0.33	0.00	0.00
4.00	-0.33	2.67	-4.00	0.67	-2.00	0.67	-0.67	3.33	0.00	-2.33	0.00	-1.33	-2.67	-0.67	0.00	1.33	0.00	-4.00	0.33	1.00	4.00	-0.33	-1.00	2.67	2.33	0.00
6.33			-5.33			3.33			-2.33			-4.67			1.33			-2.67			2.67			5.00		
1			3			2			2			3			1			3			2			1		

	DBB	DB	CMR	Open Tender	RFP	Direct Selected	Fixed Rate	Fixed Price	GMP
DBB	-	-	-	1	-1	-1	1	1	-1
DB	-	-	-	-1	1	1	-1	1	1
CMR	-	-	-	1	1	-1	-1	-1	1
Open Tender	1	0	1	-	-	-	1	-1	1
RFP	1	1	0	-	-	-	1	-1	-1
Direct Selection	-1	1	-1	-	-	-	1	1	-1
Fixed Rate	1	0	-1	1	1	1	-	-	-
Fixed Price	1	1	-1	-1	-1	1	-	-	-
GMP	1	-1	1	1	-1	-1	-	-	-

Fig. 6. 1st Alternative Process

2. Compare the chosen alternative to its corresponding alternatives from different parameters by utilizing Interdependent Relationship Matrix (Figure 7),

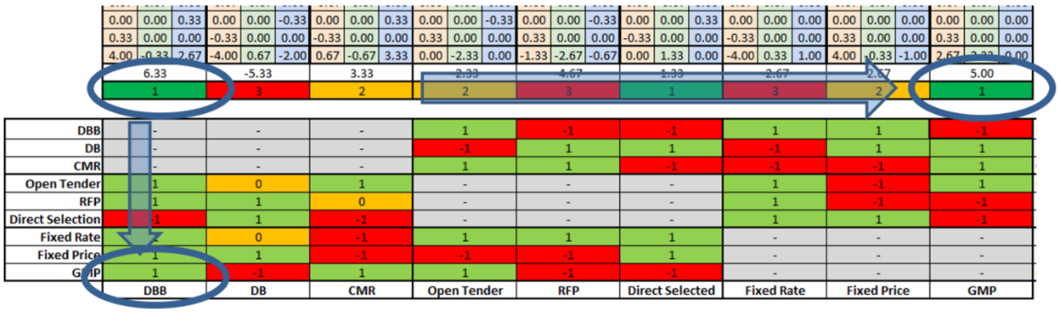

Fig. 7. 2nd Alternative Process

3. Seek the best possible compatibility by referencing to Selection Priority (Figure 8), starting with 1st priority and then moving downward towards lower priority if no feasible match is found,

Selection Priority:		
Corelation behavior	Alternate Rank	Priority
1	1	1
1	2	2
1	3	3
0	1	4
0	2	5
0	3	6
-1	1	7
-1	2	8
-1	3	9

Fig. 8. Priority Selection

4. The best compatibility will be your 2nd chosen alternatives,
5. From the 2nd chosen alternatives to seek the 3rd alternatives by assessing compatibility from Interdependent Relationship Matrix referenced to selection priority as done in Step 2 and 3,

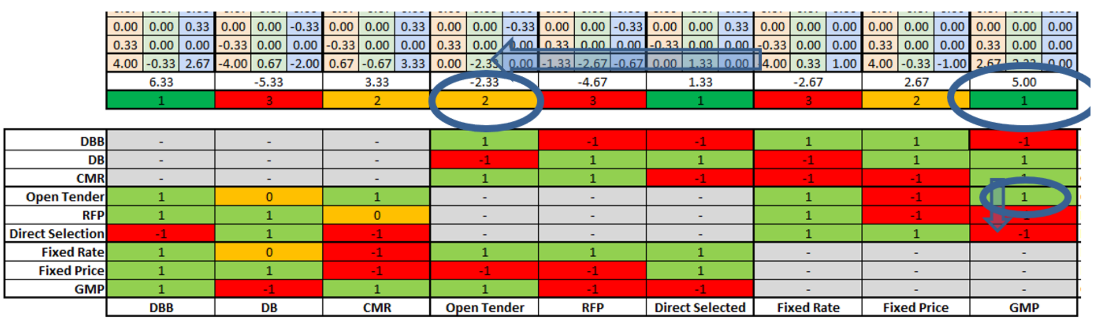

Fig. 9. 3rd Alternative Process

6. Finalize your best possible combination of project delivery method, procurement method, and contract type, each being one of the three alternatives.

5. Conclusions

This report provides a framework that suggests a best suitable project delivery system that considers the benefits and risks between project delivery method, procurement method, and contract type which is measured in a cross-functional relationship. It would help owners to decide on multiple aspects for determining the optimal project delivery system of a specific project. In addition, the framework would facilitate comparison through 3 factors governing project

success. Actualizing the impact of each contributing factor, this tool accommodates the multiple perspectives for each different parameter.
However, this study will still need more improvements to help achieve practicality. The current state of the tools act as a baseline as it is considering the general checklist questions to position the project. To act more extensively, checklist questionnaire could be developed for considering more specific issues pertaining to the project condition. Future recommendation of the study would be to try utilizing the framework against multiple case studies. It will help in evolving the framework by incorporating several factors that might have been overlooked.

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Innovative Stay-in-Place Formwork Method for Reinforced Concrete Columns

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Abstract

Recent earthquakes at Pohang in Korea have caused significant damages to existing reinforced concrete (RC) structures. Particularly, piloti columns of RC structures suffered considerable damages. The objective of this research is to review the feasibility of an innovative stay-in-place formwork method using the Textile Reinforced Concrete (TRC) for RC columns in order to improve seismic performance and reliability. The scope of the study includes 1) a development of a concept for TRC stay-in-place form for RC columns, and 2) designing and manufacturing of TRC form modules. It is expected that structural damage of the property, human injuries or loss of life caused by future earthquakes can be reduced by improving the seismic performance using TRC site-in-place participating form, which can also save the social cost for the recovery from the disaster.

Peer-review under responsibility of the scientific committee of the Creative Construction Conference 2019.

Keywords:Textile Reinforced Concret ; Stay-in-place Form; Seismic Performance; Reinforced Concrete Column; Earthquake; Piloti Structure

1. Introduction

1.1. Background

On November 15, 2017, a total of 31,000 structures, including houses, shops, and factories, were damaged by a 5.4-magnitude earthquake in Pohang, South Korea. Among the facility damages, the column failures of the reinforced concrete piloti structures of low-rise houses were severe. The causes of the damages of the piloti structures were shown to be associated with the insufficient facility design and construction procedure, such as the eccentricity of the core wall, the shortage of the shear reinforcement of the column, the non-compliance of the detailed construction standard, etc. [1]. Seismic design standards have not been properly applied to the piloti structures, and construction quality control has not been properly performed to ensure seismic performance of such structures. Fig. 1 shows several example cases of column failures of piloti structures in Pohang. In the columns of the piloti structures, the designed cross section was not properly secured due to an excessive concrete cover of 100 mm thickness and an inclusion of drainage pipes in the column member. The spacing of the shear reinforcement far exceeded the design standard of 152 mm to 260 mm. The poor anchorage of tie, which did not to comply with hook detail standards were also observed.

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The first floor piloti columns of RC structure are the core members to support the entire structure. In the event of an earthquake, the vulnerability of the piloti column can be directly linked to the risk of property damage and loss of life because it could be extended by the collapse of the entire structure. In other words, securing the structural performance of the piloti columns is a prerequisite for ensuring the stability of the entire structure. However, in the case of domestic small piloti buildings, seismic performance of structures has not been fully guaranteed as confirmed in the earthquake damages in Pohang. The root cause of this problem can be pointed out to the poor working environments in which small low-rise piloti structures are constructed. Most of these facilities are constructed by small-to-medium sized construction companies with insufficient construction management capacity or employing low-skilled workers. It may often be observed that the details of design documents are insufficient, the workers' understanding of the seismic details is unsatisfactory, or construction criteria are not completely met. Consequently, it is assumed that the variation of the seismic performance of the piloti columns is considerably large at the small low-rise piloti structures in Korea.

1.2. Objective and Scope

An alternative technology to improve the seismic performance of domestic RC piloti structure, which is currently exposed to the risk of earthquake, is urgently needed. The purpose of this study is to investigate the technical validity of the method to secure the seismic performance by using the permanent stay-in-place formwork using the textile reinforced concrete (TRC) for the columns of RC structures. The scope of the study includes 1) a development of a concept for TRC stay-in-place form for RC columns, and 2) designing and manufacturing of TRC form modules.

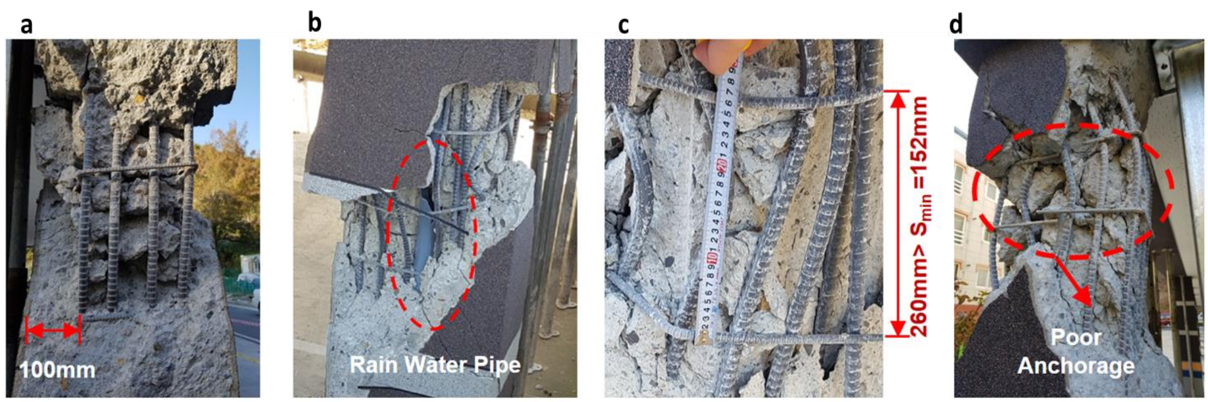

Fig. 1. Examples of Column Failures of Piloti Structure in Pohang, Korea: (a) excessive concrete cover; (b) inclusion of rain water pipe; (c) inappropriate spacing of ties; (d) poor anchorage of ties (non-appliance of hook detail standards)

2. Concept of Stay-in-Place Formwork and Textile Reinforced Concrete

Conventional temporary formwork methods of RC structure have long been a target area of innovation in construction sites. There are two underlying reasons. First, there is a certain limitation to shorten the construction duration since the RC work is sequentially conducted such as in the order of temporary formwork installation, reinforced bar assembly, concrete pouring and curing, formwork removal, and finishing work. Second, there is a difficulty in managing the quality of work depending on various working conditions due to the characteristics of outdoor environment as the most of related work are performed on-site, leading to a large amount of deviation in work quality. Moreover, the outstanding issues of the shortage of skilled workers and the aging of workers also exacerbates the problem of construction cost increase in Korea. Thus, many attempts have been constantly made to develop a more innovative stay-in-place formwork system method, which can be carried out in parallel with precise factory pre-fabrication and site installation of the RC member required in the structure while shortening the construction duration by skipping the formwork removal process. Early attempts were to develop a permanent formwork system using general single materials such as wood, steel, etc. However, practical use of such system was constrained to a limited extent due to the diverse problems such as formability, durability, and economical feasibility.

Development of stay-in-place formwork systems with new composite materials were attempted. Studies on the development of permanently fixed formwork using fiber-reinforced-polymer based concrete have been performed [2, 3]. However, they have not yet been put to practical use due to the drawbacks of low resistance to fire despite their excellent structural performance. Another attempt to develop a stay-in-place form was to utilize Textile Reinforce Concrete (TRC). The concept and advantages of TRC can be summarized as shown in Fig. 2. TRC can be defined as a composite material in which continuous textile fabric are integrated with portland cement and a cement matrix composed of fine aggregates. The TRC possesses high tensile strength due to the characteristics of textile fibers, and also has excellent advantages with respect to high durability, corrosion free, formability, and light weight.

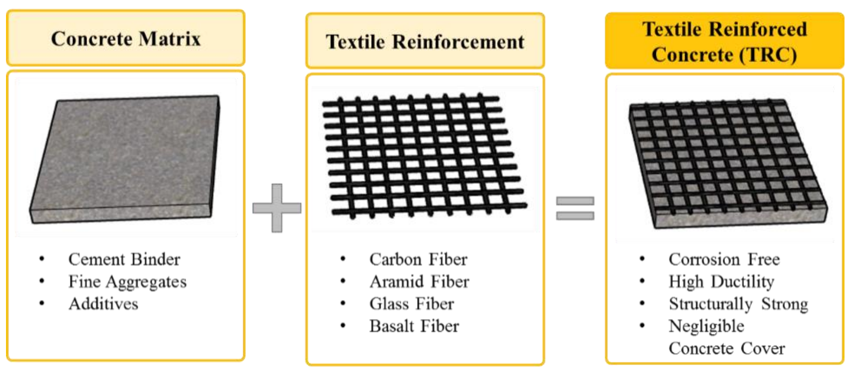

Fig. 2. Concept and advantages of Textile Reinforced Concrete

As shown from a result of flexural and tensile tests at the material level in Fig. 3, a brittle failure was observed for control experimental specimen without textile fabric, but a progressive failure was observed for the TRC panel, which showed high flexural strength and toughness. By utilizing these advantages of the TRC panel, it is possible to provide the formwork function for construction of reinforced concrete structure and also to improve the seismic performance of the structural member.

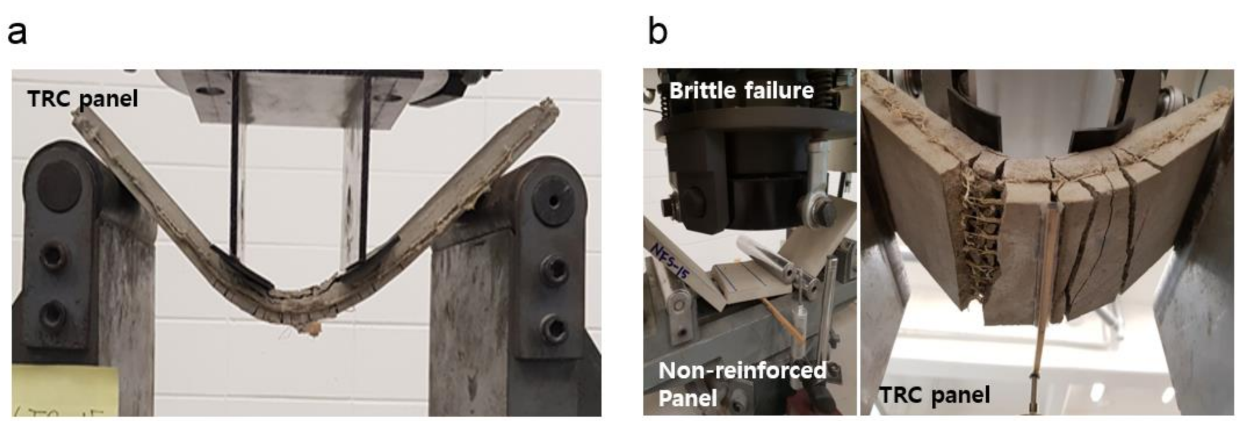

Fig. 3. Tests of TRC panel: (a) flexural test; (b) comparison of failure modes between non-reinforced panel and TRC panel

In the past studies, the development of stay-in-place formwork using TRC has been conducted around horizontal members such as slabs and beams [4, 5, 6, 7]. Recently, experimental works on the performance of TRC stay-in-place formwork applied for a vertical member such as columns [8, 9] and an asymmetric shell structure [10] have also been performed. Existing studies have demonstrated that the structural performance of a column using TRC is superior to that of a conventional RC column through the experimental test of specimens. On the other hand, there has been no study on the design and construction methodology of the stay-in-place form module targeting for the commercialization of such technology by considering constructability and economical feasibility. In particular, there have been no studies on the stay-in-place TRC formwork method to improve the seismic performance of piloti columns that are vulnerable to earthquakes. In this study, the prototype of the TRC stay-in-place modular member was designed and fabricated based on the results of reviewing the validity and applicability to the piloti columns.

3. Design and Manufacture of TRC Stay-in-Place Formwork Modules for Concrete Columns

3.1. Modulization of TRC Form

The division of the panel module was considered for 1) the convenience of transportation and operation, 2) the efficiency of production and installation, and 3) the time and cost. This study focuses on the development of stay-in-place formwork for rectangular columns which is most frequently used in small residential facilities. For casting and curing of concrete, the TRC permanent forms should be located at four sides of columns and assembled. The weight of TRC form was estimated to be approximately 53 kg when the TRC permanent form with thickness of 40 mm, height of 1,000 mm, and the cross sectional area of 400 mm x 400 mm was placed without any division. Considering the weight of the member and the convenience of transportation, it is advantageous as the division of the panel section increases. For example, as shown in Fig. 4, when dividing into two sections, the weight of the unit member becomes 27 kg, and when divided into four equal sections, it can be reduced to 13 kg. However, if the section division of panel modules results in the increase factory manufacturing time and site installation (due to the increased time for assembly of each forms), the efficiency of the work is reduced and the costs of production and installation of TRC formwork members are increased. In addition, there is a disadvantage in that the stability of structural elements may be decreased due to an increase in the number of joint elements of the TRC modules by the sectional subdivision. Therefore, no sectional division in the shape type module was considered in this work for the development of TRC stay-in-place formwork for RC columns.

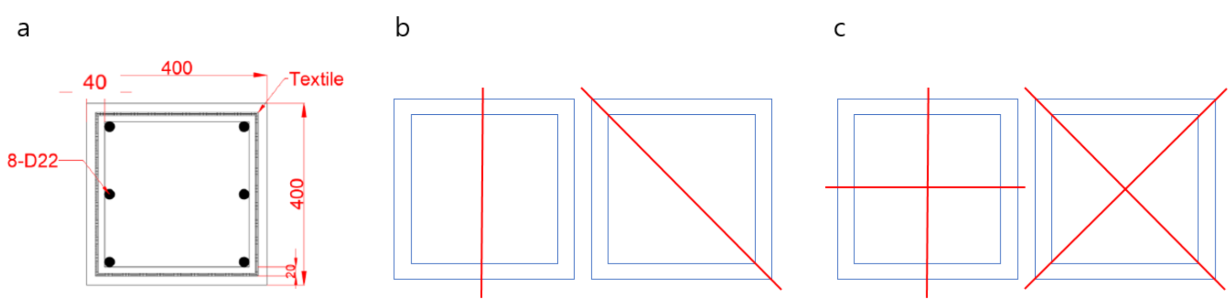

Fig. 4. Review of Module Division Alternatives of Textile Reinforced Concrete: (a) no division (53kg); (b) 2 sections (27kg); (c) 4 sections (13kg)

Since the design of the building (especially for the height of floor) is different from each other, there is a problem with difficulty in standardization for the production of the members in advance. If the TRC stay-in-place form elements can be mass-produced by modularization, the time and expense for manufacture and installation can be saved significantly. In order to realize these benefits, this study suggests a vertical modularization scheme which allows a standard prefabrication of bottom module regardless of the floor height, as shown in Fig. 5. The TRC form module applied on top of the RC columns is prefabricated in a custom-made modular method according to the planned floor height. Concave and convex grooves at both ends of the modules are designed for the easy connection of the upper and bottom TRC modules on site. In addition, the pre-processed holes for the insert of shear key to fasten the upper and bottom modules are suggested.

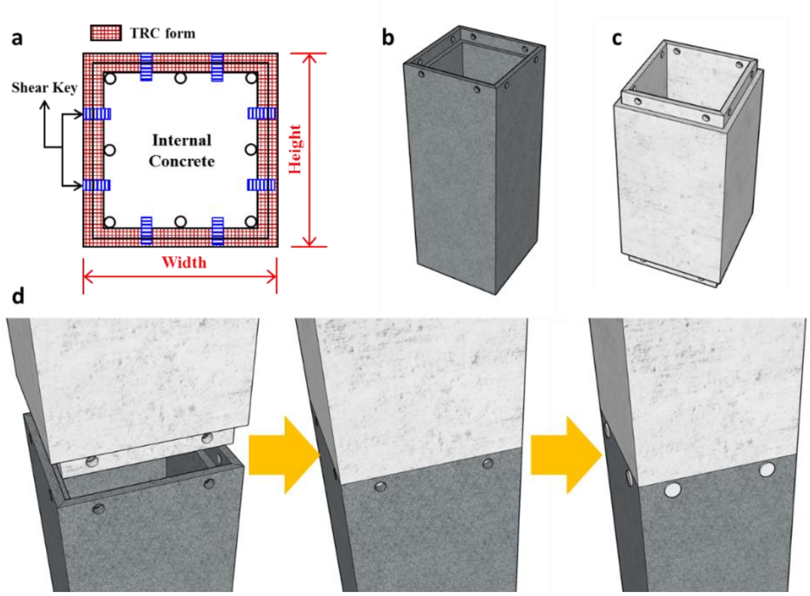

Fig. 5. Development of TRC Form Module: (a) section of TRC form module; (b) bottom module; (c) upper module; (d) connection between upper and bottom modules

3.2. Manufacture of TRC Form Module

A mold for the production of TRC stay-in-place form module was designed and manufactured as shown in Fig. 6. The mold of TRC shaft form module was made of steel for durability and repeated use. Outer panel of the mold can be folded out to facilitate easy removal of the form after textile fabric installation, casting and curing of concrete. The inner panels of the mould is able to be folded inward when the bolts are unscrewed to minimize damage during removal work of the TRC shaft module.

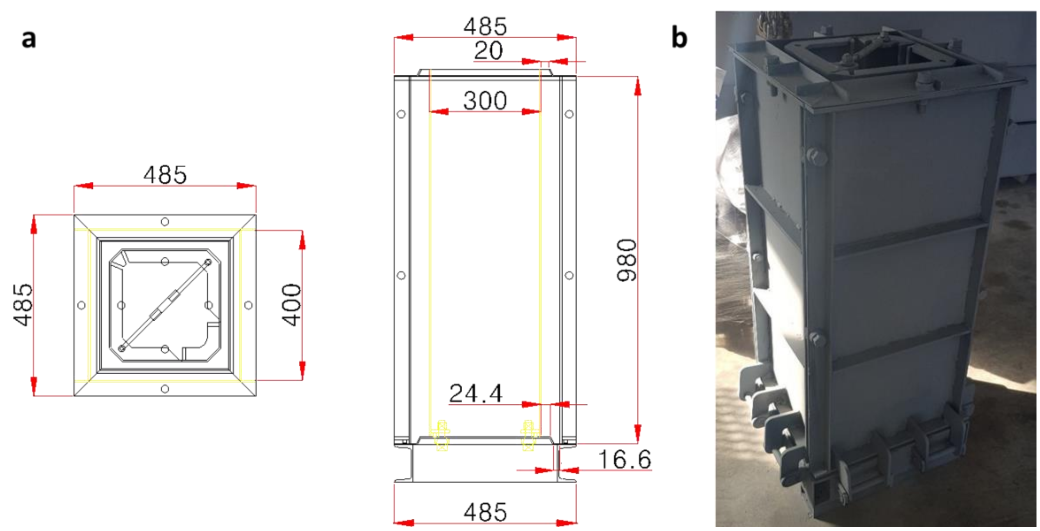

Fig. 6. (a) Mold design for TRC site-in-place form; (b) Mold production for TRC stay-in-place form

A prototype TRC stay-in-place was produced as shown in Fig. 7. After opening the outer panel of mold, textile fabric was installed at the planned position by using inner spacer at the mold. The outer panel of the TRC mold was sealed in order to place fresh concrete. When the outer and inner panels were removed after curing for a sufficient period of time, the TRC stay-in-place form module was finally produced.

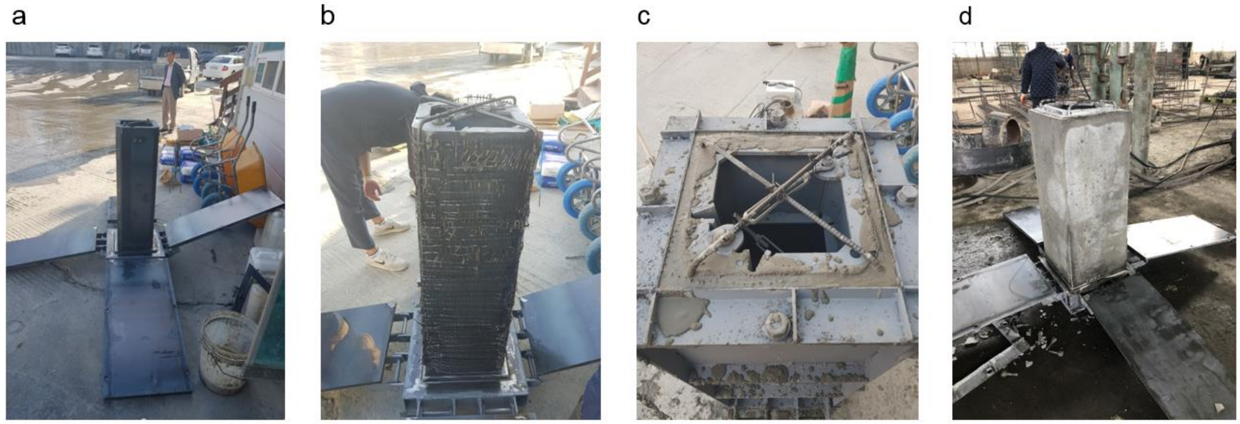

Fig. 7. (a) Opening of TRC form mold; (b) installation of textile; (c) placing of concrete and curing; (d) completed TRC module shaft

4. Conclusion

In this study, the design and construction method of the innovative stay-in-place formwork to secure the seismic performance of the column of the RC structure was proposed by utilizing a new composite material of TRC. The rectangular cross section of the TRC stay-in-place form module was proposed. The division of the TRC stay-in-place module was not considered due to the constructability and the stability of structural elements after the connection of form elements. In addition, in order to adapt for the changes in the height of RC columns, modularization method of TRC form divided into upper and lower part was proposed. In the following study, evaluation of seismic performance of RC columns using TRC stay-in-place formwork, evaluation of field applicability for practical use, and comparative productivity and economic evaluation work compared with the conventional methods are planned to be carried out. It is expected that it will reduce the damage of structures due to natural disasters such as earthquakes through securing the seismic performance through the TRC stay-in-place form, and also reduce the social cost for recovery after the disaster.

Acknowledgements

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Radiant Wall Cooling for Sheltered Structures in Underdeveloped Countries in Extreme Climates

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Abstract

Hot and harsh climates of many underdeveloped countries are extremely problematic. People find themselves battling heat exhaustion and premature death caused by unforgiving heat events. The aim of this research is to improve the thermal comfort of Haitian residential shelters through testing radiant wall cooling and sustainable design principles. The research is limited to concentrate on small sheltered structures typically found in locations of low-income families, specifically in Haiti. The researchers focused on through literature review by investigating (1) previous case studies, (2) industry standards means and methods of sustainable construction, and (3) current trends in the host nation residential construction, striving for the most plausible acceptance of residential hybrid technology. The study includes the assemblies of a composite design--i.e., corrugated metal, bamboo and water delivery--to function and achieve a betterment for an interior shelter climate, by constructing a small replica test model. The limited scale model was constructed and tested in an effort to prove or disprove the theory of thermal comfort utilizing radiant wall cooling in hot climates. The model used both host nation common materials, and limited outside technology; thus enabling ease of accessibility to the native people. The testing of the models occurred in three phases; two of which are presented in this paper. The use of Fluke thermal imaging and Fluke temperature and moisture instrumentation were utilized collect data from the models. The findings of this study conclude the integration of such material assemblies are appropriate to change the performance of the interior shelter space during hot climates. It is with these efforts and findings the researchers are encouraged and look to open dialogue among architectural, engineering and building professionals to create new levels of thinking into more exploratory means per each individual host nation's challenges. These hybrid methods of construction may quickly be implemented and continued long after humanitarian efforts have departed.

Keywords: Bamboo: Haiti; Radiant Cooling; Sustainable; Thermal comfort

1. Introduction

Hot, harsh climates of many underdeveloped countries are extremely problematic. Although the definition of a shelter can be most anything; there lies one component of the shelter which is frequently challenging in providing comfort for those residing and far from electricity: a controlled interior climate. People find themselves battling heat exhaustion and premature death caused by unforgiving heat events. Attention to interior comfort and health is as important as the basic shelter itself, but where most fall short is the marriage between the two; structure and thermal comfort, pending geographic location of sheltered needs.

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In an effort to reduce heat related deaths and possibly some diseases, the interior climate and way the shelter can be constructed using materials composed primarily of the host nation may be able to reduce this chain. If there is an ability to create an assembly of components both natural, and with limited manufactured material; there may be a central core to the basis of impoverished nation residential design [1]. Organizations from years past have accomplished many feats in helping those in need, but there lies one common shortfall, the people. Despite all the success stories over time, some of these efforts are short lived, or until the funding and outside resources are depleted. Thus, the native people are left to fend for themselves, not knowing how to build the western influenced shelters. It is said the only successful improved shelter will be one made from the host countries natural resources, while staying within the methods of construction familiar to those who live there with limited outside resources, which may be readily available after support aid has subsided [2].

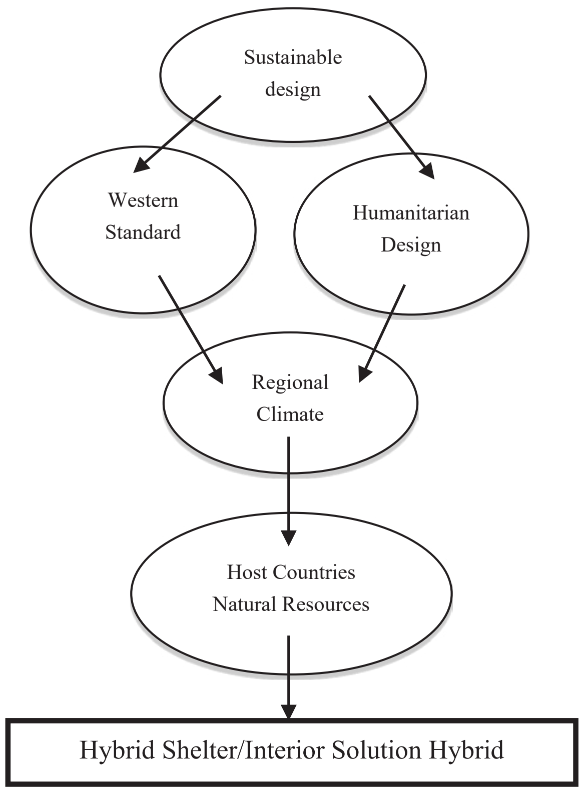
The ability to run small water filled lines within the foundation, walls, and/or roofs has been experimented to various degrees in efforts to find an alternative way to cool or heat interior spaces without the high cost of energy. Radiant cooling is a different approach than the conventional “Western” method of forced air, split system cooling you typically find in most homes in the U.S.; it performs by way of convection. As the hot air rises, the cooler air falls to lower levels of the interior space near most areas inhabited by occupants [3]. As the interior water circulates within the inter floors, walls and sometimes roofs, it is always within a set limit of temperature settings; thus the more the water is moving, the cooler the water can be maintained from the regulated source. The aim of this research is to improve the thermal comfort of Haitian residential shelters through testing radiant wall cooling and sustainable design principles. The research is limited to concentrate on small sheltered structures typically found in locations of low-income families, specifically in Haiti.

2. Literature Review

Previous investigations into building envelope radiant cooling are the launching pad to create a composite assembly, which may work within the restrictions of host nation’s architectural developments [4]. Harnessing the power of the sun is always looked upon favourably to reduce the dependency of manufactured energy [5], and enlightens many components into one large resource to assist in the design of a sustainable systems. Other resources in the host countries basic resources and methods of construction may be investigated to assure, methods of new assemblies may likely be utilized or experimented for general acceptance.

Haiti over many years has faced natural disaster challenges such as earthquakes and hurricanes; often leaving many residents without basic shelte [6]. Many previous attempts to rebuild in Haiti have seen both success stories and tragedies [2]. Teaching the local construction trades of an undeveloped country new Western standards, does not always lead to an improved structure. As with most humanitarian efforts many structures have been built by the local trades using Western like standards, but tragically have failed in some cases under dynamic loading [7]. These studies may touch on some construction detailing areas, but will not digress into lateral and dynamic impacts of small sheltered structures. By integrating more professional developmental with proven technology, cultural building techniques, and resources typically found in host nations; other related issues may see resolutions [8]. The ability to work along host nation's primary needs, in addition to giving them tools that they can embellish their life styles will pay dividends for years to come.

The International Federation of Red Cross and Red Crescent Societies are organizations which have given years of support towards areas in need around the world; and in doing so have established a base line criteria towards design, which are typical needs to be address. Six standards are described in the International Federation of Red Cross and Red Crescent Societies. Standard number 4, under the Shelter and Settlement section, calls for “sufficient thermal comfort and fresh air among other general building criteria.” Other publications, by the International Federation of Red Cross and Red Crescent Societies, Traditional Shelters-Eight Designs; attempt to design and construct to area specific climates and traditions, but do not elaborate on how, only indicating ventilation [9]. The criteria by the Red Cross and Red Crescent Societies gives the presumption of open thinking in terms of humanitarian problem solving while working alongside local nationals [8]. Influences towards betterment in most Western humanitarian efforts includes sustainable design, Western standards of design, humanitarian design standards, regional climates, and host country's natural resources as illustrated in Figure 1.



(1)

Figure 1: Influences toward betterment

Water for example is always a concern pending geographical locations; however, areas such as Haiti have the ability to use rain, humidity condensing collectors or saltwater for the purpose of radiant cooling, thus in this case may not be a major dilemma. The single most important possible issue is condensation due to the humid climate of Haiti [10] and the ability to control the effectiveness of the wall assembly. Although there are other fabricated components, which may eliminate or reduce this occurrence, the cost implications may not be advantageous. Further, any desiccant humidity controls product will only be a hazard to children if solution efforts stray this direction in the future.

Further research and development into radiant heat and cooling has occurred for many years [4]. The radiant cooling approach issues identified stem from lack of industry use or willingness to adapt a new methodology in the West specifically; despite this technology having been used in European countries for many years past [4]. In an effort to arrive at a plausible solution, the focus of this study will evolve around a methodological approach using a base scale model approximately thirty inches in width, height and depth. The culmination of design standards and other applicable elements shall be in some cases assumed in the construction of the model (i.e. structural and wind loads) due to condense time of analysis [11]. It shall be noted this study will not attempt to solve all aspects of the interior thermal comfort theory; only to raise awareness of the plausible solution and applications still awaiting to be discovered, if certain marriages of technology and materials are further explored. The study focuses on assemblies of common materials in conjunction with limited solar resources, in order to achieve a betterment of the interior living environment [12]. Further analysis will sustain some common traditional practices, but introducing uncommon methods of interior environmental cooling.

3. Research Methodology

A plan was formulated from the knowledge gained in the literature review to test specific materials. The study includes the assemblies of a composite design to function and achieve a betterment for an interior shelter climate, by constructing a small replica test model. The proposed composite testing material for the model is based on two basic materials most prevalent in the country of Haiti: corrugated metal and bamboo. Corrugated metal is found in most countries; however, even if this material is not an option, the use of any metal panel may produce similar result. Since corrugated metal comes in a variety of depth, 7/8" will be used for testing and model purpose. The other material found in Haiti is bamboo. Since this country has seen heavy deforestation over many years, the new and promising material can provide ease of use for just about anything buildable. Sizes of bamboo are in the range of approximately 1-1/2" in diameter, but may vary plus or minus 1/2" in diameter.

The limited scale model was a box shape, approximately 30 inches width x 30 inches deep x30 inches height as shown in Figure 2. This sample box utilized 7/8" corrugated metal on three sides of the box, with bamboo facing all exterior sides of all three walls. Over the bamboo was 1/2" polystyrene insulation material with an R-4 insulation value to represent other plausible material used for insulating walls, such as palm leaves or green vegetation potentially found in most tropical areas. Integration of a small solar powered submergible fountain pump was installed for limited water movement; this assembly will replicate those limited fabricate components easily found in most parts of the world.

The form of information gathering was broken down into three simple phases with the use of a sample model. The testing of the models occurred in three phases. The use of Fluke thermal imaging and Fluke temperature and moisture instrumentation were utilized collect data from the models.

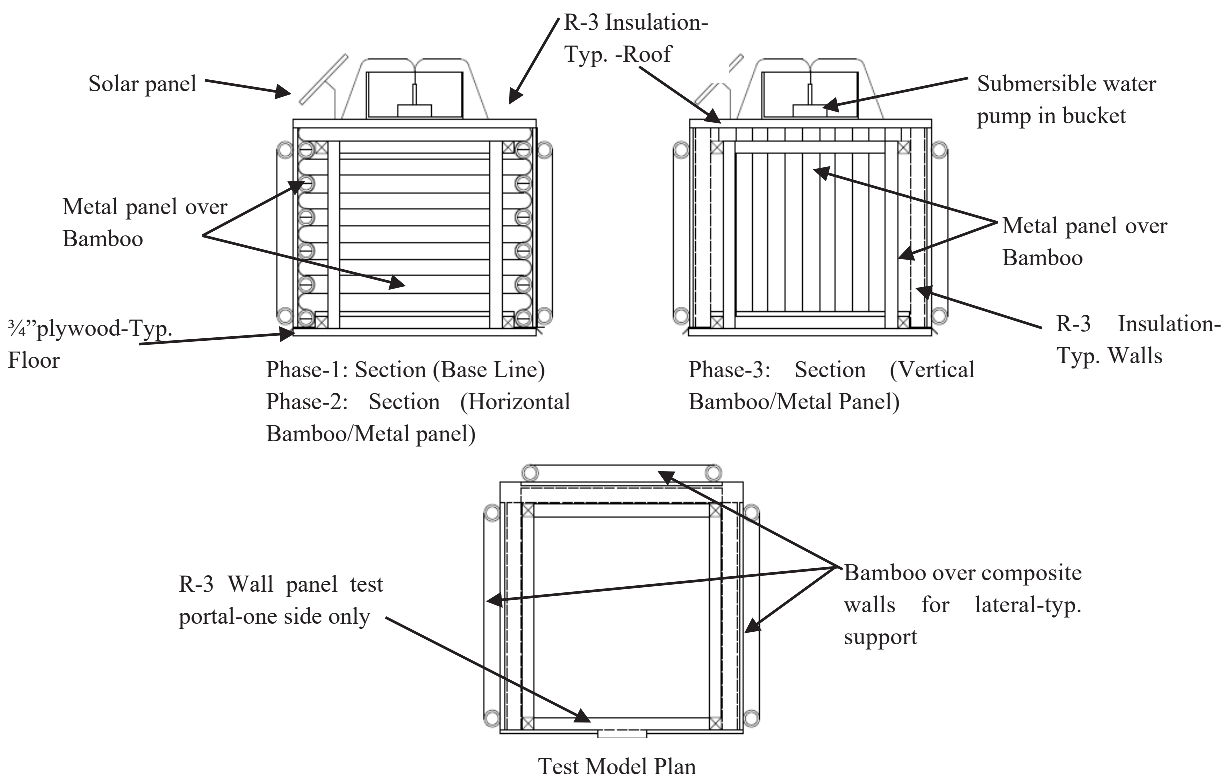


Figure 2: Testing Model - 30"x30"x30"

(2)

The limited scale model was constructed and tested in an effort to prove or disprove the theory of thermal comfort utilizing radiant wall cooling in hot climates. Analysis from fundamental of material usage in addition to performance of the interior space occurred in this study. A benchmark, limited-scale model was established to create a better understanding of other field data being gathered for interpretation. Further, differing configurations were attempted to attain the best performance of wall assemblies. As with differing configurations, came additional manufactured components, which may or may not be the best fit to ensure the least amount of outside material is used [13]. The comparison of each configurations using a lesser manufactured reliance on assembly evaluated compatibility with host countries social acceptance [2].

Given the data from the base scale model, these data marks will be charted for comparison to determine best plausible solution for thermal comfort. Other benchmarks will be evaluated for conformance to ensure if the best solution will be the most acceptable to host counties cultural building trades. Other graphical information will be presented to witness phase changes occurring within the wall components under no improvement, followed by two tested assemblies, which resemble each other, but differ slightly [14, 15].

Experimental research with a field constructed scale model provided realistic data given the complexity of the components being installed in an unlikely ensemble. Although this method of experimentation can be somewhat subjective, the application use of the snowball-cluster sampling effect is well justified in the given proposed study [16].

The method of information gathering will be broken down into three simple phase (Table 1) with the use of a sample model. The three phases are: Phase-1 (Baseline), Phase-2 (Horizontal Bamboo/Corrugated Metal panels) and Phase-3 (Vertical Bamboo/Corrugated Metal panels). Note Phase-3 is not included in this study and will be included in the data set in future works. Small water fountain pumps powered by solar panels were used to facilitate the movement of water within the bamboo pipes. Temperatures readings are recorded during most afternoon times of higher average temperatures.

Table 1. Phase temperature readings approach

Phase	Reading type	Testing method	Unit
Phase-1 Baseline	Exterior temperature readings	FLUKE Temperature	Fahrenheit (F)
	Interior temperature readings	FLUKE Temperature	Fahrenheit (F)
	Interior humidity readings	FLUKE Humidity	Percentage (%)
	Exterior Infrared Imaging	FLUKE Camera	
	Panel Condensation	Visual examination	Yes or No
	Solar Water Pump	Visual examination	Yes or No
Phase-2 Horizontal Bamboo	Exterior temperature readings	FLUKE Temperature	Fahrenheit (F)
	Interior temperature readings	FLUKE Temperature	Fahrenheit (F)
	Interior humidity readings	FLUKE Humidity	Percentage (%)
	Exterior Infrared Imaging	FLUKE Camera	
	Panel Condensation	Visual examination	Yes or No
	Solar Water Pump	Visual examination	Yes or No
Phase-3 Vertical Bamboo	*Not included in this particular study analysis*		

Information derived from the aforementioned phase testing was incorporated into a series of simple graphs, each depicting their own results. Phase-1 established a base line comparison, both exterior temperatures with interior temperatures and interior humidity. The tracking information gave indications to any performance increase is the temperature delta between the exterior and interior temperatures. Functionality of wall components was evaluated on ease of construction and delivery of water through bamboo pipe systems; both horizontally (Phase-2) and vertically (Phase-3) to measure overall performance. Solar and water pump components will be evaluated for basic functionality given the placement and simple delivery of water with the bamboo pipes.

4. Results and Findings

The testing for all phases were compiled into an excel spreadsheet for simplicity and visual comparative analysis. Basic calculations showing Phase-1 (Baseline) vs. Phase -2 (Vertical bamboo) attest on how each performed within their design limitations.

4.1 Phase-1 (Baseline)

The establishment of the Phase-1 Baseline was accomplished before any water was introduced into all bamboo piping, thus the elimination of bamboo fibers becoming water logged after water drainage. Under the Phase-1 Baseline, the exterior and interior temperature delta was seen at approximately 6.7 degrees cooler inside the scale model box (Table 2). Since the test was being performed in October, temperature fluctuations were more common than ideal testing performed in the summer months with more constant high temperature readings.

Table 2. Baseline Readings for Phase-1

Exterior Temp (F)	Exterior Humidity (%)	Interior Temp (F)	Interior Humidity (%)	Exterior/Interior Temp Delta	Panel Condensation (Y/N)	Water Temp	Solar Water Pump (Y/N)	Water Flow Problems (Y/N)
99.3	28.60	92.6	29.60	6.7	N		N	N/A

4.2 Phase -2 (Horizontal Bamboo) – Average Temperatures

Once the Phase-1 Baseline was established, testing began with introducing water into the bamboo pipes during varying times during the day. The strategy behind this method was to capture performance with both higher temperatures and lower temperatures during the course of mid-day till late afternoon. Thus, temperature deltas could be evaluated on how much an impact was being made during the differing demands on the wall panels. Under the Phase-2 test, readings were an improvement from the Phase-1 baseline on average of 10.10 degrees less than the exterior temperature; an increase of 3.40 degrees interior temperature reduction from the Phase-1 Baseline model (Table 3).

Table 3. Phase-2 Readings (Horizontal Bamboo) – Average Temperatures

	Exterior Temp (F)	Exterior Humidity (%)	Interior Temp (F)	Interior Humidity (%)	Exterior/ Interior Temp Delta	Panel Condensation (Y/N)	Water Temp (F)	Solar Water Pump (Y/N)	Water Flow Problems (Y/N)	Notes
Test-1 2 Oct, 14:00	105	24	96.2	27.20	8.8	N	86.3	Y	Y	Upper tube water flow issue
Test-2 2 Oct, 15:00	105	26.60	94.1	31.30	10.9	N	85.6	Y	Y	Upper tube water flow issue
Test-3 3 Oct., 17:00	93.2	37.10	85.1	44.70	8.1	N	83.7	Y	Y	Upper tube water flow issue
Test-4 4 Oct., 11:00	103	41.10	90.4	47.40	12.6	N	89.7	Y	Y	Upper tube water flow issue

4.3 Phase -2 (Horizontal Bamboo) – Average High Temperatures

The Phase-2 model was also evaluated by utilizing the two average higher temperature readings given during those peak temperature time periods. As a result, the Phase-2 high temperature readings produced and improvement from the Phase-1 baseline on average of 9.85 degrees less than the exterior temperature; a decrease of 3.15 degrees interior temperature reduction from the Phase-1 Baseline model.

Although Phase-1 provided minimum R-3 polystyrene insulation, its performance only resulted in minimally reduction of the interior temperatures during peak time of afternoon heat. Phase-2 on the other hand proved to show improvements, reducing the interior temperature further by a few degrees, however the function of the system can be problematic due to different sizes of bamboo and providing enough water pressure to ensure all bamboo pipes have water.

Water coverage within the bamboo pipes proved to be the underlying factor by physical attributes of both the bamboo pipe and the curvature of the corrugated metal panels. Under Phase-2 horizontal test, the bamboo panels are running horizontally with the corrugated metal panels; this only enables half-filled bamboo pipes to transfer radiant cool bamboo surface to only 1/4 of the metal panel wall.

5. Conclusions and Future Research

The findings of this study conclude the integration of such material assemblies are appropriate to change the performance of the interior shelter space during hot climates. During phase testing of model, those materials such as corrugated metal panels and bamboo may be found in Haiti. Betterment of interior temperatures as it compares to exterior higher afternoon temperatures was achieved in the Phase-2 model testing.

A limitation of this study includes the use of polystyrene insulating wall which is not prevalent as a material to most residence in Haiti. There is however, the ability to use about any insulating material or dried vegetation to provide similar results of the polystyrene insulation board used during testing. Other native materials would have to be used to replicate insulating values. Small solar panel pumps are common, and may be found in most countries, but system may still operate under natural water head pressure, thus the solar water pump may be an option.

Attention to the amount of thickness must be adhered, the more material the better the performance of the bamboo and metal panels. Further, despite all phase models showing exposed polystyrene insulation, insulating materials should always be covered with a rain screen material for added protection. Additional material critical from a water infiltration into the interior space is base wall flashing towards the exterior; absence of this simple metal component will be introduce potential overfilled or cracked bamboo water within the cavity and into the shelter, thus opening cause for illness.

Due to the limited amount of time during the academic semester, further testing scenarios could not be examined. The researchers continued this study with Phase-3 testing. As well as recommending to reiterate the phase testing. The testing in this study were conducted in the changing seasons from summer into fall; during multiple tests, typical high temperatures most common in Texas are stable for only a few hours during the day, which were recorded but may vary from one day to another. The best times to test these phase assemblies are during late spring and summer months; preferably in a southern climate to measure in-depth wall performance since conditions as this will be similar to Haiti.

It is with these efforts and findings the researchers are encouraged and look to open dialogue among architectural, engineering and building professionals to create new levels of thinking into more exploratory means per each individual host nation's challenges. These hybrid methods of construction may quickly be implemented and continued long after humanitarian efforts have departed.

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The Delunay Triangulation in the design of architectural gridshells

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Abstract

The design of original gridshell forms has become an increasingly complex process, which aims to search for unique spatial systems which are also effective engineering solutions – both architecturally as well as structurally. The search for synergistic solutions which combine the aesthetics of the form with structural logic is supported by modern bionic tendencies. They allow the reproduction of the organic shapes not only by means of proportions, but also by mimicking the biological developmental processes and by understanding the logic of the structural forms occurring in nature. The analogies between architectural design and morphogenesis of biological forms have increased the interest in bionic structures as a whole. The improvement of digital tools based on algorithmic codes has enabled architects to implement their bold designs based on the logic of Nature's technologies.

One of the most interesting bionic methods of discretization of structural surfaces is Delaunay triangulation, a dual graph of the Voronoi Diagram, which describes the divisions of the plane and space found in nature. Examples can be found in the patterns of a dragonfly wing, giraffe's mottled skin or a turtle's shell. The Delaunay divisions are more and more often used in the design of architectural forms based on gridshells. Solutions for such systems are obtained through generative modeling, and the algorithm responsible for the surface discretization is incorporated into 3D modeling programs. A big advantage of using digital generators in the search for optimal architectural and structural solutions is the ability to model multiple-variants and to the easily modify them (the models result from iterations of the entered numerical data).

The paper will present the trends in the development of spatial bionic gridshells based on Delaunay triangulation, as well as the results from own research on selected gridshells. The undertaken analyses compare material efficiency on two analyzed cases.

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Keywords: Surface discretization, generative modeling, Delunay

1. Introduction

Increasingly complex structural forms are a characteristic feature of modern architectural design. The original, bionic shapes of the 21st century buildings are created as a result of the creative search, but also the changing philosophy in architectural design – surprising in terms of plasticity, technical and technological rationality. Computational calculation methods lead to the improvement of modeling tools as well as the fabrication of building elements and even whole objects. Currently, architects can design spatial forms with very complex structures. Algorithmization of

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the supporting design tools provides new opportunities, but also creates new challenges, including rationalization, which necessitates a greater focus on conceptual modeling in the design process. The article analyzes open roofs that are small scale architectural objects with a relatively uncomplicated function. The design of structural forms in relation to the contemporary computing tools and the known mathematical models is increasingly more important. The interdisciplinary design of gridshells leads to sophisticated structural systems, which are more and more often characterized by unobvious, complex shapes, with their geometries referring to free fractal structures, sometimes going beyond the paradigms of Euclidean geometry[1]. In the search for the new architectural gridshell solutions bionic patterns play an important role. With the development of research tools we gain the knowledge about the formation of the surface structures of living organisms. The knowledge becomes an inspiration in the design of load-bearing structures and also in the broadly understood civil engineering and materials science.

2. Optimisation in architectural and structural designing

Optimization is an important element in the design of modern technical architectural structures. In the context of creative designs and exploration, at the intersection of architecture and structure, *form finding* and *topology* deserve special attention. To paraphrase Confucius, the American mathematician Andre Cherkaev compares optimization to: "*searching for a black cat in a dark room in a minimal time*"- assuming that the search range corresponds to a room filled with furniture. This sentence was originally written down by Confucius and it read: *„The hardest thing of all is to find a black cat in a dark room, especially if there is no cat in it”*. To find the cat, however, minimal lighting is needed. There is no golden ratio, and the skillful use of possible variants is most important - this is optimization according to A. Cherkaev. With regard to architecture, optimization should be understood as the process of rationalizing technical solutions by undertaking solutions which are the most beneficial at the early design stage. The more advanced the building process is, the more expensive the building optimization is. In search for savings in contemporary architecture, an increasingly frequent phenomenon is a multivariate concept deepened by thorough analysis carried out on several levels - these include structural analysis (structural optimization), energy, urban planning, materials, etc. All these elements have an impact on the form - its technical and technological efficiency and artistic expression. Yet another development can be observed in the parameterization of elements involved in the design of the form which allows to iterate the design process which lead to the "emergence" of the field of effective solutions. Regardless of the chosen technique, achieving the intended goal requires a well-thought-out sequence of actions and the use of the right tools at the right time. Optimal form finding with the use of parametric tools requires "algorithmic thinking”[2].

To optimize the structural forms, the form needs to be determined along with the rational cross-sections of the elements, which is related to the choice of appropriate materials. The rational design choices and following the systems of forces have the greatest influence on the aesthetics of form. In this context, the following issues deserve special attention: design of the form and discretization of structural surfaces. One of the more interesting directions of exploration are topologies describing structural deformations[1], which can lead to rational solutions. A more famous example of the use of topology in architecture is the catenary curve described in the Renaissance (the first sketches of suspended chains can be found in the works of Leonardo da Vinci). The Simon Stevin manual from 1634 states that the rope hanging freely between supports is shaped parabolically. At the same time, Christian Huygens described the geometry of the catenary curve (Latin *Catena* - chain), proving that the curve, similar in its shape to a parabola, is an independent creation. In the last century, Antonio Gaudi, whose work on chain models lasted 10 years, was the architect who contributed most to the development of the research on catenary curves. Among others, the physical model of the *Sagrada Familia* in 1:10 scale was created at that time.

One of the more important issues in the optimal design of structural forms is the discretization of the surface. The selection of the appropriate method of division, as well as the indication of the mesh density has a fundamental impact on the efficiency of the structure

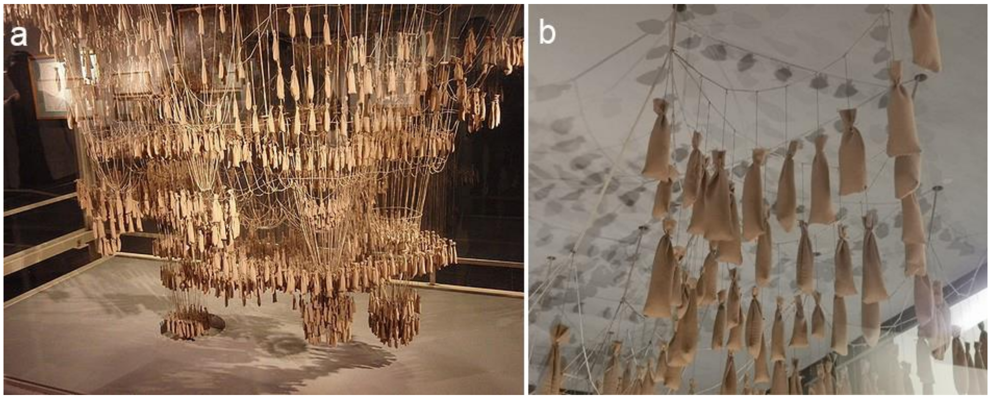

Fig. 1. A. Gaudi – model research; (*a)* 1:10 model of *Sagrada Familia*; (*b*) detail of the binding of the weights;

Apart from the Finite Elements Method, which leads to effective structural solutions, many other methods are still used to discretize contemporary surfaces. One of them is *Delaunay's Triangulation*, which uses the bionic pattern of the Voronoi Diagram - being its dual graph. An accessible tool for delineating *Delaunay* divisions is the Grasshopper plug-in for Rhino program, which allows the discretization of the surface based on the adopted geometric parameters. However, the modeled gridshell must then be subjected to structural analysis - this requires the cooperation between two different programs. In addition, the model determined on the basis of the geometry and intuitive assumptions is subjected to further optimizations. It can be done with *Dynamic Relaxation* - an additional function of the Gasshopper plug-in. It is a numerical method of computational modeling, the aim of which is to find such a geometry that all forces are in equilibrium. This can lead to rationalization of solutions, including reduction of the total weight of the structure, which has a direct impact on the reduction of the amount of material used and reduction of later construction costs. This method makes topological transformations of a given structure, leading to relaxation of nodes.

Referring to selected mathematical models and methods of optimization of structural surfaces, the effect of relaxation of the nodes on the structure of the roofing was examined. The examples of structures that were created thanks to the Grasshopper plug-in for Rhino program and the Kangaroo2 plug-in for Grasshopper (this plug-in allows simulation of gravitational forces on the structure, thanks to which it is possible to create catenary models), were then analyzed structurally using Robot Structural Analysis programs.

Access to computer aided design tools significantly accelerated the search for the optimal structural form. An example of such a tool is the Grasshopper-Karagaroo2 plug-in used in the following tests, which assigned loads imitating physical forces to the pre-created mesh. The ability to change the working force, the extensibility of the elements and the placement of the supports, generate a system of solutions that have been subjected to structural analysis in the next phase. The study compares the grids generated by means of dynamic relaxation with the grids projected onto the created geometry. The results of the gridshell analysis described below were built on these basic assumptions (Fig. 2).

The structure is a roofing (open roof) on a square plan with a total area of 900.0 m²;

- the roofing is based on three supports, determined using the Voronoi formula(in the Grasshopper plug-in for Rhino). The supports are positioned in such a way that they form a triangle similar to an equilateral one, and at the same time they are centers of fields with an area of 300.0m² each. Static support scheme - articulated joints;
- *Delaunay triangulation* was used to determine the structural divisions of the surface, assuming that the maximum beam length was 4.5 m.

Two analyses of the effectiveness of particular geometries of forms(examination of the effect of the deflection deflection of the structure) and the metric of bar division (maximum length of bars: 3.0m, 3.5m, 4.0m, 4.5m, 5.0m) were carried out on the example of Delunay meshes dropped on a chain model or relaxed on a chain model.

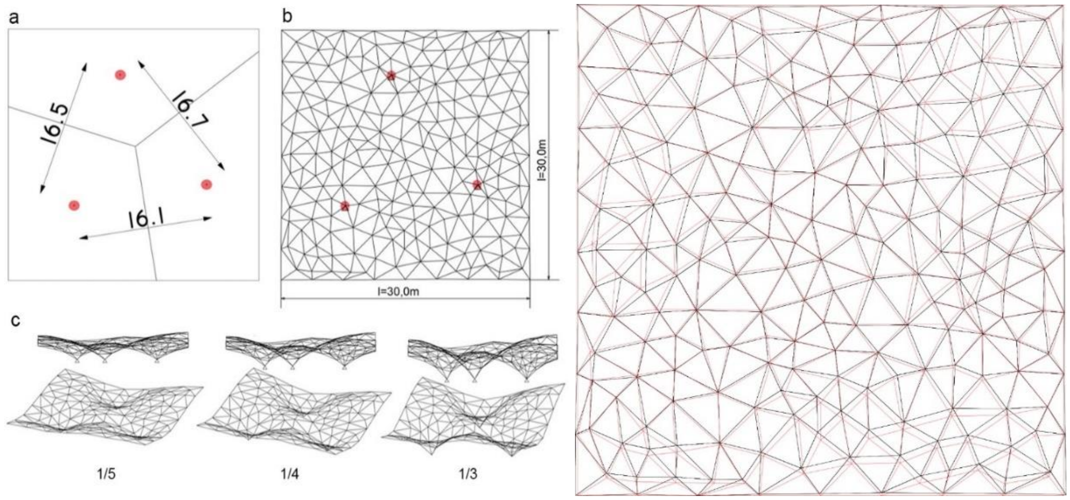

Fig. 2.(a) scheme of supports location and determining the Voronoi polygons of a comparable surface; (***b***) Diagram of Delaunay divisions with the maximum 4.5 m long beams;(c)the curvature heights; (d) illustration of overlapping variants C from Analysis 1 and Analysis 2 (the 1/3 ratio), showing the degree of changes in the geometry of Delaunay divisions (red) due to topological transformations using the logic of chain models (black)

2.1. Analysis 1

The *Delunay triangulation*, initially applied to a flat geometry, was then projected onto the displaced geometry (node points were only moved in the Z axis so that they were on the surface of the curvature) determined according to the catenary model principles:

- the deflection is determined by the height of the middle point to the average support span ratio. The following three options have been proposed depending on the height of the center point (Fig.2.):

Variant A1 - height to the support span ratio: 1/5
Variant B1 - height to the support span ratio: 1/4
Variant C1 - height to the support span ratio: 1/3

Uniform closed THEX (hexagonal tubes), TRON (round tubes) and TREC (rectangular tubes) profiles made of S355 steel were adopted for all the layouts. One of the assumptions was the homogeneity of the structure, hence for each of the variants one of the most effective external dimension of the profile was selected (regardless of the fact that individual beams in the structure do not work equally). At the same time, it was possible to change the wall thickness of a given profile – though from the outside the profiles should look the same. Due to the same starting geometry of all variants, a maximum deformation value of 19.5 cm was assumed. In the search for effectiveness, the minimum mass criterion for the entire roof was adopted. Due to the variable roof area (caused by the change of the deflection), the weight per 1.0 m² of the roof was also considered as an important parameter.

Two profiles differing in wall thickness were selected for all variants. The most effective variant, based on the adopted weight criterion was Variant C1 (total weight of 73 253 kg). Although this variant was characterized by the largest area of the roofing, it was characterized by the smallest weight per 1.0 m² of the roof, which amounted to 72.38 kg / m² - about 30% less than the most unfavorable option. Additionally, in all the analyzed variants, the TRON (round) steel profile was the most effective.

Table 1. Results of analyzed structures where rods were projected on a geometry with a maximum projected length of rods of 4.5m

The curvature height to the support span ratio	Adapted profile(type and dimensions in mm)	Maximum deformation [cm]	Total length of the rods [m]	Total weight [kg]	Surface area [m^2]	Weight per m^2 of the surface [kg/m^2]
1/3	TRON 406x8,0 406x6,3	18,4	1536,09	97 337	943,75	103,13
1/4	TRON 355x6,3 355x8,0	19	1558,42	92 454	965,17	95,79
1/5	TRON 323x5,6 323x6,3	19,4	1593,86	73 253	1012,01	72,38

*2.2. **Analysis 2***

Analysis 2 adopts a similar geometry for the gridshell form. Nodal points have been released. Subjecting the mesh to dynamic relaxation resulted in the nodal points being able to move not only in the Z axis, but in accordance with the acting forces. Thanks to the freed the nodes the structure could better adapt to the given loads(Fig.2d).

Through the generative algorithm, the adopted variants change the geometrical layout to a small degree - changes are unnoticeable in the scale of the entire gridshell. As the constructional analysis shows, the change in the structural layout has significantly improved the results. Analysis 2 adopts variants analogous to Analysis 1 with the same center point height to the support span ratio:

Variant A2 - height to the support span ratio: 1/5
Variant B2 - height to the support span ratio: 1/4
Variant C2 - height to the support span ratio: 1/3
Similarly to Analysis 1, homogeneous closed profiles were adopted by selecting from the THEX (hexagonal tubes), TRON (round tubes) and TREC (rectangular tubes) profiles made of S355 steel. In this case, for all the variants, the round tube also proved to be the most effective. Variant C2 (with the 1/3 ratio) reached the smallest total mass (analogously as in Analysis 1) equal to 54 094 kg. The mass ratio calculated per 1.0 m² of the roof was 53.46kg / 1.0 m², which is almost a 40% better result than the worst version in this analysis.

Table 1. Results of analyzed of catenary relaxed structures with a maximum projected length of rods of 4.5m.

The curvature height to the support span ratio	Adapted profile(type and dimensions in mm)	Maximum deformation [cm]	Total length of the rods [m]	Total weight [kg]	Surface area [m^2]	Weight per m^2 of the surface [kg/m^2]
1/3	TRON 335x8 335x6,3	16,1	1531,06	83 974	945,73	88,76
1/4	TRON 323x6,3 323x5,6	16,4	1548,05	68413	968,64	70,68
1/5	TRON 273x6,3 273x5,0	16,6	1581,37	54 094	1011,95	53,46

2.3. Comparison of results

In Analysis 2, there is a significant improvement in the efficiency of structures in relation to the layouts in Analysis 1. There is also a visible relationship between Analysis 1 and Analysis 2, where all the results of A2, B2, C2 are much more favorable.

Variant A: weight improvement: the A2 variant is 13,390 kg lighter than the A1 variant, which results in 13.76% lower material consumption;
Variant B: weight improvement: the B2 variant is 24,041 kg lighter than variant B1, which results in 26.00% lower material consumption;
Variant C: weight improvement: the C2 variant is 19 159 kg lighter than variant C1, which results in 26.15% lower material consumption;
It should also be noted that the C variants in each of the analyzes achieve the smallest total weight, despite the largest length of beams.

3. Conclusion

The inspiration of bionics in contemporary architecture and civil engineering is an interesting phenomenon. The use of mathematical models mapping the morphology of living organisms may lead to the rationalization of technical solutions when it is justified and implied by structural logic. An example of such are the analyses carried out in the above study - where the use of the catenary model was dictated by the model of physical forces acting on the designed structure. The conducted analyses also confirmed that modifying the form "exerts" a great influence on the structural efficiency. For this reason, the pursuit of shape optimization should be carried out at an early stage of creating the architectural concept. The aesthetic evaluation of structural forms is subjective. However, in designing of the spatial form through morphological analysis, one can find an increased share of logic in the creation of a work of art - assuming that what is functional, rational, etc. is also beautiful. However, can the ethos of creative freedom in architectural design be enclosed in the definition of rationalism?

Quo Vadis Architectura? Will the search for beauty lead to rationalism? Or perhaps logical thinking is the starting point for the creation of perfect works? Regardless of the answer, it should be stated that the search for beauty of the structural forms does not always lead to logical solutions. On the other hand, the search for logical solutions can lead to bionic systems whose beauty results from the beauty of Nature.

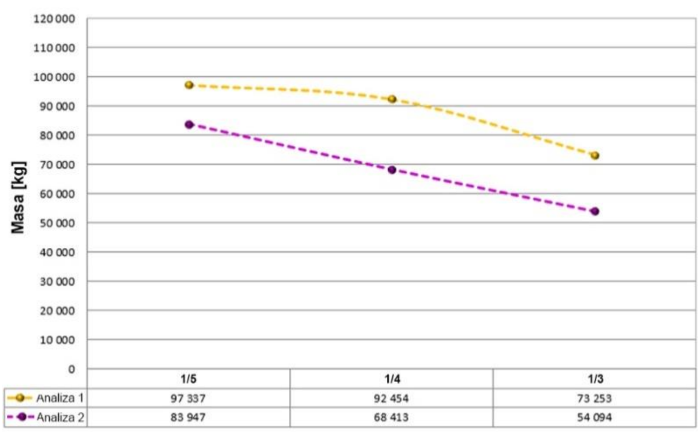

Fig. 5. List of results obtained from the analysis of individual variants from Analysis 1 and Analysis 2

Topological optimization of the structural surfaces using logic of catenary models allowed to reduce the consumption of structural material by 21.97% on average.

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"Parametric design is defined here as a process based on algorithmic thinking, which allows the expression of parameters and principles which define, code and explain the relationships between the design intention and the design response. This process is justified in architectural design when there is such a relationship between the elements of the project, which requires manipulation of information about the complex geometry of the form and its structure. Parametric design is not a new concept and has always been a part of architectural design. "

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The role of product eco-labels in realising the greening agenda of the construction industry

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Abstract

The proliferation of green products/materials in the construction industry (CI) have been traced to the global attention on sustainability. However, greenwashing and continuous specification and use of unsustainable construction products/materials keep restraining the transition of the industry towards the sustainable path. Hence, the need for efficient and effective assessment and labelling tools to provide reliable information about the environmental attributes of construction products/materials. This study sets out to examine the impact of green product eco-labels in achieving the sustainability goals of the CI. An extant review of the literature was conducted on the various available green product eco-labels in use in the industry. Findings revealed two significant types of eco-labels namely: single attribute and multiple-attribute. Specification and use of construction products/materials with household-named and reliable eco-labels by construction professionals and stakeholders is recommended, as this step has the potential of mitigating the negative environmental impacts of the CI.

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Keywords: assessment tools; built environment; construction materials; green building; sustainability.;

1. Introduction

Products, materials and technologies specified for use in any infrastructural or building project play a cogent role in achieving the sustainability objectives of such project. To achieve sustainable design and construction goals, the United States Green Building Council (USGBC) considers the choice of construction materials as a fundamental factor [1]. The study of [2] also identified the specification/selection and use of products and materials with unfavourable impacts on the environment as a significant constraint to the transition of the construction industry (CI) towards the global sustainability movement. Products and materials used to construct, operate and maintain infrastructures over their life-cycle contribute to their degrading impacts on the natural environment [3], thus impeding their sustainability goals. Based on past predictions of sustainability proponents and various researchers, pollution, greenhouse gas emissions, and loss of biodiversity are few of the effects of the continued utilisation of unsustainable products and materials over the years. For example, Sick Building Syndrome has been attributed to the off-gassing of volatile organic compounds (VOCs) from modern finish materials such as carpets, paints, adhesives and vinyl among many others [4]. Also, the traditional Portland cement contributes significantly to the atmospheric concentration of GHGs through limestone decomposition, fossil fuel combustion, the breakdown of raw materials and energy consumption during its production

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[5]. The extraction, processing, production and transportation processes involved in the manufacturing of construction products and materials have also contributed to the gradual depletion of worlds natural resources. As a strategy for curbing the spread and continuous adverse impacts of the CI, the concept of sustainable construction (SC) is introduced.

The terms sustainable construction (SC), high performance, green building (GB), and environmentally-friendly building amongst others are often used interchangeably to describe the transition of the CI towards achieving sustainability [3,6,7]. The focal point of SC is to proliferate the efficient use of water, energy and materials while minimising its footprint on the environment, human health and safety [8]. SC is premised on the provision of socially, technically, and economically pleasing and blooming human environment with minimal or no harm to the natural environment [9]. However, despite the global recognition of the importance of GB, the demand, adoption and implementation are still at its infancy due to lack of knowledge, awareness, sustainability measurement tools and eco-friendly construction materials [10,11,12]. To achieve the sustainability of building projects and construction products/materials, energy and water efficiency are some of the standards to be met, leading to the development of sustainability assessments. This paper, therefore, evaluates the roles played by product eco-labels in realising the sustainability goal of the construction industry. Related studies on construction products/materials eco-labels are done and presented. The final section presents an overview of the existing eco-labels, concludes the study and after that proffer recommendations.

2. Overview of sustainability evaluation tools

The development of several sustainability evaluation tools is aimed at achieving GB projects. Sustainability evaluation tools offer standards and guidelines in measuring how green or environmentally friendly a building is while also supplying recognition and validation of such claims [4]. These tools help in addressing environmental issues during construction processes and assessing the environmental performance of buildings. They are voluntary tools developed in each country/region to support the development of sustainable buildings, apart from Sustainable Building Challenge and Living Building Challenges which are regarded as international rating standards. While some of these tools are country specific (applied within their country of origin), others are applied both in their country of origin and adopted by other countries, an example of which is Building Research Establishment Environmental Assessment Method (BREEAM).

According to [13], prominent among the sustainability assessment tools include BREEAM, Leadership in Energy and Environmental Design (LEED), Comprehensive Assessment System for Built Environment Efficiency (CASBEE, Japan), Green Mark Scheme (Singapore), Hong Kong Building Environmental Assessment Method (HK BEAM), Green Building Index (Malaysia), Green Building Council of Australia Green Star (GBCA, Australia), Green Globes, and Pearl Rating System for Estidama (Abu Dhabi Urban Planning Council). However, most commonly used and widely accepted among these assessment tools are LEED and BREEAM [7]. The development of these assessment tools is for different types of buildings (i.e. residential, industrial, commercial) and urban developments which are assessed differently and with a different criterion. They are deployed to evaluate and provide verifiable sustainability ratings [14]. [15] also listed EcoQuantum (Netherlands), KCL Eco (Finland), Bees (USA), and Beat (Denmark) as other available assessment tools. These assessment tools, however, play a prominent role in advancing the growth of sustainable buildings/projects in their respective countries of use as well as globally.

2.1. BREEAM

Building Research Establishment Environmental Assessment Method (BREEAM), developed in the United Kingdom (UK), is one of the first and most utilised ratings systems in the world for evaluating the compliance level of projects to sustainability guidelines and criteria [3,16,17]. BREEAM assesses the environmental performance of building projects under ten major categories namely: health and well-being; pollution; ecology; water; materials; waste; management; transport; energy; and land use. The rating scale used are certifications of pass, good, very good, excellent, and outstanding [17]. Trained and licensed assessors provide the assessment of BREEAM ratings by producing a report containing an outline of the project's performance and overall rating. It has influenced the development of other rating tools such as LEED, Green Globes, and Green Star. There has been a consistent update of BREEAM version to address the different categories of project types such as educational, residential, industrial and infrastructural projects. Till date, BREEAM has developed versions for infrastructure projects (BREEAM Infrastructure), mixed-use projects (BREEAM Bespoke), communities or regeneration projects (BREEAM Communities), commercial building projects excluding residentials (BREEAM In-use), new building projects and new-build extensions to existing building projects (BREEAM New Construction), and refurbishment or fit-out projects (BREEAM Refurbishment and Fit-out).

2.2. LEED

Leadership in Energy and Environmental Design (LEED) is developed by the United States Green Building Council (USGBC) as a green building certification program, and it is best known and prominent in the U.S [17]. LEED seeks to measure and assess environmental performance in seven categories as follows: sustainable sites; water efficiency; energy and atmosphere; materials and resources; indoor environmental quality; innovation in design; regional priority (added in 2009); and locations and linkages [3,4,17,18]. Just like BREEAM, LEED is updated from time to time and newer versions established to address the different types of building projects ranging from infrastructural, residential and commercial projects among others.

2.3. Green Globes

Presently deployed both in Canada and the United States, the framework of Green Globes is based on the BREEAM rating system. The non-profit Green Building Initiative (GBI) is the licensor of Green Globes in the U.S [18]. This tool can be used to assess the impact of project decisions on point scores with the ratings expressed as one, two, three or four globes representing increasing levels of environmental performance [3]. Green Globes assesses environmental performance under seven key categories namely: site; energy; water; indoor environment; emissions, effluents and other impacts; resources; and project/environmental management [4,18].

3. Sustainability evaluation tools: classification and categories

From literature, there are two main classifications of sustainability assessment tools namely: criteria-based system and life cycle assessment methodology (LCA). The criteria-based tools are those that assign point values to selected criterion (i.e. BREEAM, LEED) while the life cycle assessment methodology (i.e. EcoQuantum, KCL Eco) uses different weighing techniques based on different rationale for evaluation to be deployed for selection of building design, material, and local utility options [15]. Due to the complexities in the greening of infrastructural projects, these rating tools address different aspects and categories. For example, GBCA Green Star rating tools tackle nine aspects which are material; emissions; transport; energy; indoor environmental quality; management; water; land use and ecology; and innovation [13]. On the other hand, the Malaysian Green Building Index, derived from the Australian Green Star System and Green Mark Singapore, addresses six vital benchmarks namely: material and resources; indoor environmental quality; water efficiency; energy efficiency; innovation; and sustainable site planning and management [8]. A careful analysis of the constituting categories of these assessment tools reveals material as a significant and indispensable part that is common to all. This discovery, however, substantiates the fact that the kind and attributes of materials and products selected for use in a project go a long way in determining whether it will achieve its sustainability objectives.

4. Products/materials evaluation, rating and labelling systems

There are quite a few assessments, rating, and labelling systems/tools for evaluating material and product sustainability (also referred to as eco-labels). As listed by [3], the following are the most common, popular and widely used, with their corresponding country of origin: Blue Angel Certification (Germany); CarbonFree Certification (USA/UK);

China Environmental Logo (China); Building Research Establishment Certified Environmental Profile (UK); EcoLogo (Canada); EcoMark (Japan); Eco-Leaf (Japan); Energy Star (USA); EU Ecolabel (European Union); Environmental Choice (New Zealand); Good Environmental Choice (Australia); Forest Stewardship Council (FSC) Certification (USA); GREENGUARD (USA); GreenSeal (USA); Hong Kong Green Label (Hong Kong); GreenLabel Plus (USA); National Sanitation Foundation (NSF) International (USA); Korean Ecolabel (Republic of Korea); Nordic Ecolabel/Swan (Denmark); Thai Green Label (Thailand); Singapore Green Label Scheme (Singapore); WaterSense (USA); Water Marque (UK); Scientific Certification Systems Recycled Content (USA); and Water Efficiency Labelling and Standards (WELS) Scheme (Australia).

These tools offer significant ways of verifying and understanding the numerous characteristics affecting material and product sustainability [16]. They also help to provide users with core information on the source, content, performance, and impact of such material and product on the human and natural environment. According to [4] and [19], material and product evaluation, rating and labelling systems fall into two categories namely: multiple-attribute rating system (which consider and verify several attributes) and single-attribute rating system (which verify and focus on only one attribute). An example of the multiple-attribute rating system is GreenSeal (USA) and Environmental Choice (New Zealand) while that of the single-attribute rating system is Energy Star (USA). Certification, assessment, rating and labelling tools have, therefore, become the most effective way of authenticating the sustainability attributes of construction products/materials. These tools also serve as an avenue for regulating the green market, specification and use of materials with adverse impacts on the environment.

5. Benefits and goals of products/materials eco-labels in achieving sustainability

Several benefits are accrued to embracing the use of products/materials with eco-labels in achieving the sustainability objective of the construction industry. The definite transition from the traditional and unsustainable construction materials is believed will result in a continuous rise in demands for those that are sustainable and specifically eco-friendly. Eco-labels have become mechanisms by which the environmental performance of construction materials and products are measured and ascertained. To aid the transition of the CI from the traditional state to the sustainable one, materials/products eco-labels aims to protect the green market, expand the green market, curb greenwashing, and reduce environmental impacts.

5.1. Green market protection

Several construction products/materials have laid claim to a certain level of been green without the application of any standard, hence the reason for the development of products/materials rating systems, standards and guidelines (eco-labels). However, the development of materials and products eco-labels are out of the need to protect the green market from construction materials that are unsustainable for use. According to [20], these product eco-labels ensure the protection of the green market in the following way:

- Ensures the confidence of consumers (construction professionals and stakeholders) in materials/products quality;
- Provides consumers with detailed information about the materials/products quality;
- Prevents the influx/import and circulation of inappropriate or low-quality construction materials/products;
- Facilitates and simplifies the specification of materials/products for consumers;
- Stimulates the acceleration of scientific and technological development;
- Contributes to the improvement of the organisational and technical level of production; and
- Contributes to lasting success and protect competition with manufacturers and suppliers of non-certified materials/products.

5.2. Green market expansion

GB has become answers to the several negative environmental impacts of the CI. With the global focus on rapid economic development of which infrastructural provision plays a key role, the adverse effects of the CI will continue to rise except the concept of GB is not embraced. The shift to GB development has now seen a significant increase in the demand for GB materials [19], owing to the understanding of their impacts on the natural and human environment. Manufacturers of green materials/products are ensuring their products are certified in other to penetrate and dominate the market and since certification is a criterion to guarantee patronage from consumers.

5.3. Curbing greenwashing

Due to the global call for the adoption and implementation of sustainable construction practices, there has been an increase in the utilisation of green products/materials. Hence, the reason for the significant proliferation of construction materials and products with false claims on their sustainability attributes which is termed “greenwashing”. According to [21], greenwashing is the convergence of shoddy environmental capacity and affirmative disclosure about the environmental performance of a product. However, [22] presented the definition of greenwashing simply as a false claim and label of products as environmentally-responsive while they are not. The intention of which is to take advantage of the booming market and demand for materials with little or no environmental footprint by flooding the green market with false eco-friendly materials/products. Adopting the use of construction materials/products certified and rated by credible eco-labels with global integrity is, therefore, a significant way of tackling greenwashing marketing tactics.

5.4. Reducing environmental footprint

The selection and use of construction products and materials that are not environmentally responsible is a significant hindrance to the successful greening of the construction industry. With the advent of eco-labels, an inventory of product/materials LCA is provided including global warming potential, emissions, resource use (weighed and absolute), embodied energy and energy consumption among many others. Construction professionals and stakeholders are therefore able to specify and use materials/products based on their environmental impact and performance as detailed by the eco-labels they possess. Embracing the use of certified/rated green building materials with the 3R (reduce, reuse and recycle) characteristics; focusing on health impact and toxicity in materials/products; and understanding and applying life cycle analysis (LCA) of construction materials/products are factors suggested by [18] to be considered by construction professionals and stakeholders in the quest to meet the greening target of the CI.

6. Conclusion and recommendations

As the adverse impact of the CI continues to be evident and bite, the role played by construction materials and products cannot be overemphasised. These materials/products are known to emit VOCs, contains non-recyclable content and hazardous substances, consumes a significant amount of energy, and generate waste. All of these impacts among many others are contributors to the environmental degradation experienced globally. In the bid to mitigate these environmental impacts of the CI, the demand for eco-friendly construction materials and building components has seen a rapid increase. The objective of this paper was to assess the role of product eco-labels in the sustainability drive of the CI while adopting a descriptive-exploratory approach.

To profitably maximise the boom in the green market, manufacturers are giving false information on the environmental performance about their materials/products referred to as greenwashing. The adoption of reliable sustainability assessment, certification and labelling tools for construction materials/products helps serve as a guide to the right specification, selection and use. While some eco-labels (multiple attribute eco-labels), such as Green Seal and Environmental Choice New Zealand (ECNZ) evaluates materials/products against several environmental standards, others (single attribute eco-labels) such as Energy Star, Basta and GRI Green Label Plus assesses only one standard (energy efficiency). Materials/products eco-labels provides consumers (construction professionals and stakeholders) with a clear understanding of the available materials/products in the green market, provides sound information on their composition, environmental performance and effect. This study is intended to benefit the CI and encourage the specification and use of certified construction materials/products. The study recommends that government and construction professional bodies should support the proliferation and uptake of certification as a yardstick for materials specification and use.

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Variable Refrigerant Flow Systems on USACE Projects

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Abstract

Variable Refrigerant Flow (VRF) systems offer a unique set of advantages and disadvantages to a designer, contractor, and building owner. With the procurement requirements for the Government, additional challenges are introduced by these systems, and the systems are currently not permitted for US Army Corps of Engineers (USACE) projects due to requirements in mandatory design criteria. This research was performed to discover the major advantages and disadvantages of these systems, and to understand why they are not allowed on USACE projects. While performing interviews concerning these types of systems, two interesting case studies that demonstrate some of the disadvantages for these systems were discovered and will be detailed in this paper. Ultimately, it was discovered that VRF systems do not meet the public law requirement to provide open protocol control systems for U.S. Military projects. While the reasoning for this research had a particular focus on U.S. Military construction, much of the information presented will also be valuable to private entities considering these systems as well.

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Keywords: VRF, Variable Refrigerant Flow, Inverter Compressor, Efficiency;

1. Introduction

VRF systems are a relatively new type of HVAC systems used in America. These systems take advantage of using a variable capacity compressor to provide a higher efficiency than can be achieved using the more standard types of compressors that have historically been used in HVAC systems like the standard scroll or reciprocating compressor. Less power is consumed by the VRF system at part load compared to conventional systems, which is due to the variable speed driven compressors and fans at outdoor sections. [1]

The potential use of VRF systems has gone through three iterations within design criteria for US Army Corps of Engineers' (USACE) projects. The three iterations will be discussed in more detail below. The current design criteria would allow the use of this technology, but there are no vendors that meet all of the prescriptive requirements, so the use of these types of systems are still essentially not allowed. VRF systems have a variety of advantages and disadvantages that will be explored in detail in this paper. Advantages range from energy efficiency to potentially being able to reduce the required height of a building due to the principles behind using these types of systems. Disadvantages range from concerns over parts and service availability due to the proprietary nature of these systems to safety concerns due to the amount of refrigerant that will be in the piping in the occupied portion of the building.

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Much of the literature for these types of systems suggest that they are among the most efficient systems available for use in the HVAC market today. So, this research was performed to provide an evaluation between the advantages and disadvantages of these types of systems with a particular focus on what benefits may be lost since the military design criteria essentially disallows these systems.

While performing interviews for these types of systems, two interesting case studies that demonstrate some of the disadvantages for these systems were discovered from discussions with maintenance and USACE staff. These case studies support the concerns raised in the USACE design criteria that do not allow these systems. The significant problem associated with these systems for military projects is the need for very thorough training for both installing contractors and maintenance staff.

2. Background

Selecting the type of HVAC system is obviously a critical decision that must be made early in the life of a project. This decision will be one of the primary factors that determines a large portion of the utility cost for the life of the building. Selecting an efficient type of system is critical as the portion of energy use in buildings that is used inefficiently or unnecessarily is 30 percent. [2] For smaller projects, options are limited due to the types of equipment that are manufactured to handle smaller loads and typically a refrigerant based packaged unit or split system will be selected. Larger projects have a wide variety of options available including constant volume systems, variable air volume systems, boilers, chillers, packaged/rooftop units, water source heat pumps, and one of the newer technologies available is Variable Refrigerant Volume (VRF) systems. While VRF systems are relatively new in the United States, they have been in use in other countries for longer durations. Variable refrigerant flow systems have been used in Japan for at least two decades and are now receiving attention in North America as a potential HVAC system choice in commercial, retail, institutional, hospitality, and multifamily residential applications. [3] One of the main reasons that a building owner may wish to use a VRF system is the flexibility that this system has to adapt to the building load. The main advantage of a variable refrigerant flow (VRF) system is its ability to respond to fluctuations in space load conditions. By comparison, conventional direct expansion (DX) systems offer limited or no modulation in response to changes in the space load conditions. [1] In other words, a VRF system can handle less than peak conditions in a building and still provide the building user with comfort which is a problem for traditional DX systems due to the inability of the system to run at a reduced capacity. Other advantages of these systems will be discussed in more detail later in this paper.

3. Purpose & Rational for the Study

As VRF systems are not currently allowed to be used for US Army Corps of Engineers' projects, there is not as much history and knowledge within the Corps of Engineers for these systems as there is for other types of systems. The purpose of this study was to explain to the reader:

- How VRF technology works.
- The options available when using VRF systems.
- The reasons that the US Army Corps of Engineers design guidance does not allow VRF systems
- The advantages and disadvantages that need to be considered when using VRF systems.

Space heating, cooling, and ventilation costs make up approximately 33% of the energy costs for commercial buildings as can be seen in Figure 1 below. [4] So, the need to find energy efficient solutions to minimize operating costs is a constant dynamic for building owners, including the Government. However, the US Army Corps of Engineers' current design guidance all but eliminates the possibility of using VRF systems, a potentially efficient system, based on the numerous strict requirements that currently no VRF vendor meets. As the rest of the commercial market seems to be shifting towards accepting VRF, it was a question as to why their use was disallowed. The VRF market was valued at $11.08 billion in 2015 and is expected to reach $24.09 billion by 2022. [5] With the use of VRF increasing in the private world, this study was performed to identify the reasons that the Corps of Engineers does not allow these systems and what potential advantages may be lost by not using these systems. This study resulted in a series of items, both good and bad, to consider when potentially considering the use of VRF systems for a project.

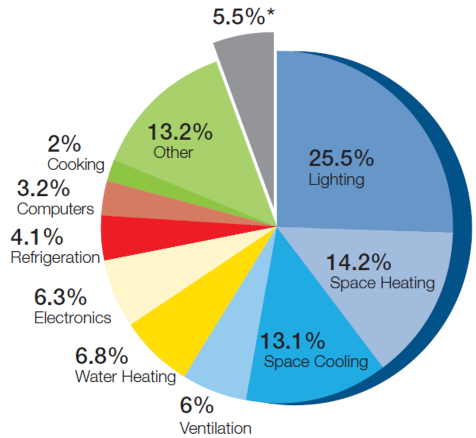

Figure 1: Commercial Primary End Use (US Department of Energy, 2008)

4. Research Design

This study evaluated various publications and vendor-based literature to provide the reader with a basic understanding of the VRF systems and the options available when using these types of systems. This study also used various literature and interviews obtained from a wide variety of industry professionals to obtain data for these systems including private design engineers, commissioning agents, maintenance staff, installing contractors, and various US Army Corps of Engineers' personnel to evaluate the advantages and disadvantages that have been experienced while designing, installing, and maintaining these systems. Finally, this study also used interviews from US Army Corps of Engineers' personnel to gain a deeper insight as to why the use of these systems has been highly discouraged within the past and current design guidance. This study used qualitative research methods to provide the reader with the desired data as explained in the purpose of this study.

5. Data Analysis

Variable Refrigerant Volume (VRV) systems were invented in 1982 by Daikin. The company trademarked the name VRV, resulting in all other manufacturers calling their product VRF. [6] There are approximately ten vendors that are competitors in the VRF market in America based on searching the internet for companies that offer these types of systems. There are significantly more companies providing these systems in other countries. A traditional refrigerant based air conditioning or heat pump system consists of one outdoor unit containing a compressor coupled with one indoor air handling unit and the units are either on or off based on a call for cooling or heating from a thermostat. A VRF system is very different from a standard refrigerant based split system in that one outdoor unit can be connected to multiple indoor units. Another substantial difference from an efficiency and comfort standpoint is that both the indoor and outdoor units in a VRF system can operate at variable capacities as the load in each zone changes.

5.1. Components of VRF Systems

VRF systems consist of an outdoor unit with a variable capacity compressor, various types of indoor units with variable speed fans, and depending on the type of system and unit manufacturer, some type of heat recovery control unit may also be present. A heat recovery control unit is essentially a box with multiple refrigerant line connections that controls the flow of refrigerant throughout the system. Data below came from reviewing literature from the following VRF manufacturer product references. [7] [8] [9] [10]

One common feature of VRF systems is there are multiple capacities available for the outdoor units. Based on reviewing various vendors' available options, this range is from as small as a 2-ton unit to as large as a 42-ton unit for a single outdoor unit. Also, multiple outdoor units can be manifolded together to make a larger system. Each manufacturer has a different limit for the number of units that can be combined, but it is typically 2-4 outdoor units.

Each of these outdoor units can be coupled to multiple indoor units. Indoor unit capacities can range from 0.5 tons to 8 tons in various configurations. Vendors have different limits for how many indoor units can be coupled together. The range was from 1 indoor unit up to typically 40-50 indoor units, but one vendor allowed up to 64 indoor units per outdoor unit. The indoor units are available in a wide variety of configurations that allows an engineer to select an appropriate unit for the type of space it is serving. Some examples of the ductless options available are wall mounted, ceiling mounted, and floor standing. There are also horizontal and vertical ducted options available. Images of a few of these typical units are depicted below in Figure 2.

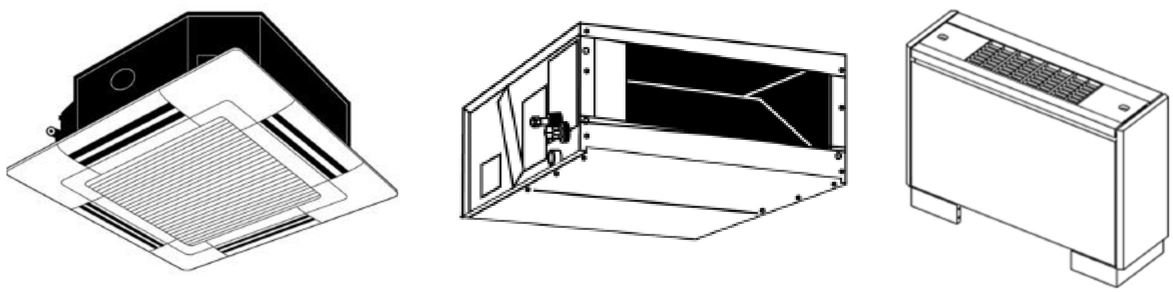

Figure 2: Indoor VRF Units: Ceiling Cassette, Concealed Ducted, Floor-Standing Exposed [11]

A final typical component is the heat recovery control unit. Each manufacturer has a branded trade name for this unit, but the operation of the unit is relatively consistent. This unit is a box with multiple refrigerant piping connections that distributes refrigerant throughout the piping network, and it is the piece that would allow refrigerant to be cycled between units that are simultaneously operating in heating and cooling without mechanical compression. This is a selling point of VRF systems in that if you have a building that has a need for both heating and cooling at the same time, it can be accomplished in a very efficient manner using this device.

5.2. Types of VRF Systems

VRF systems are available in three types of operational configurations: cooling only, heat pump, and heat recovery. Each of these arrangements has a different amount of hardware and software required for the application. The detailed design rationale for using each type of system is outside the scope of this paper, and only a basic introduction to each type of available configuration will be provided. First, the cooling only arrangement requires that all attached units be in the same operational mode and there is no heating provided by this type of arrangement. Heating would need to be provided from an additional source like potentially perimeter baseboard heaters if using this configuration. This type of system would be a potential benefit for spaces that have a constant supply of heat and no demand for additional heating like a computer room or telecommunications room. Second, a heat pump arrangement also requires that each interior unit be in the same operational mode, but this type of system has the added benefit that the entire system can be in the heating mode and the space can be heated from the VRF system versus needing a separate system for heating. This type of system would be a potential benefit for a space that has a uniform heating and cooling load throughout with no need for different operational modes in different parts of the space. The third and most advanced arrangement that utilizes the full capability of this technology is the heat recovery arrangement. Heat recovery systems are heat pump systems that can provide simultaneous heating and cooling within the same system. All indoor units connected to a heat recovery system can not only use individual control and setpoints, but they can also individually operate in heating or cooling mode at any given time. Manufacturers offer two design approaches to VRF heat recovery operation: two-pipe and three-pipe systems. [11] Knowledge of the various piping arrangements and piping connections to be used are critical to consider from a design and installation stand point and will be discussed further below under the disadvantages of these systems.

5.3. US Army Corps of Engineers Design Guidance for VRF Systems

The design and construction criteria for the Corps of Engineers is very structured. The overall design guidance for facilities is found in various documents called Unified Facilities Criteria (UFC). This type of criteria is similar to model building codes used in the private/commercial sector in that they provide higher level criteria typically focused on how the building should be designed. The more prescriptive construction specifications are found in documents called Unified Facilities Guide Specifications (UFGS). These specifications are similar to other construction specifications used in the private/commercial sector but are in general more stringent that standard commercial specifications. The information discussed below is summarized from researching archived versions of UFGS specifications and UFC design criteria.

Initially, VRF systems were not specifically mentioned in either the UFC or the UFGS documents. As the technology was relatively new, the criteria had not been updated to reflect this new type of system. There was some informal guidance circulated that pointed out that VRF systems do not meet the open protocol requirements that were found within the UFGS specification 23 09 23 for Direct Digital Control for HVAC systems. This specification was in place from approximately 2006 until 2015 when it was replaced with a very similarly worded specification. These specifications required that all equipment communicating on a control system communicate over an open (non-proprietary) communication protocol. Based on reviewing manufacturer's literature and interviews with an industry expert in this subject, there are no VRF vendors that use a non-proprietary control system. However, this information was either not well circulated, possibly waived on a project by project basis, or ignored as there have been many buildings on Army and Air Force installations provided with VRF systems since that time.

In January 2017, the UFC design guidance was updated to specifically address VRF systems. UFC 3-410-01, Heating, Ventilating, and Air Conditioning Systems, included language specifically for these systems. This was the first time that VRF systems were formally addressed in the design criteria. The language used specifically disallowed these systems to be used on Air Force projects, but the language was extremely vague for Army projects. The language that was used was: "For Army facilities, VRF systems are strongly discouraged". While the intent that the systems were not desired was clear, from a design or construction enforcement standpoint, the language was not enforceable as the use of the words "discouraged" is not contractually enforceable, so ultimately each project team and authority having jurisdiction could choose to use these systems on Army projects. The next, and current, iteration of design guidance for VRF systems cleared up the ambiguous language from the previous guidance. UFC 3-410-01 was revised in November of 2017. This guidance contains a list of nine prescriptive requirements that must be met if VRF systems are going to be used. One of these requirements is the use of an open protocol control system as discussed above. The UFC actually states that as of the publication date all known commercially-available VRF systems rely on a proprietary network. Another restrictive requirement is the use of only brazed piping connections. Based on my review of manufacturers' data, there are many of these VRF components that come standard with flared piping connections. So, while the current guidance theoretically would allow VRF systems to be used, realistically no vendor can meet these requirements. Another major concern discussed in the UFC is the amount of refrigerant that will be ran through the occupied portion of the building when using these systems that can potentially leak into the building.

As a part of this research, an interview with a USACE member that played a large part in developing these design criteria was conducted. He personally felt that the systems had great advantages and hoped that industry will adjust to meet the Government's prescriptive requirements over time. His explanation for the prescriptive requirements was that the requirement for an open protocol control system is not just a matter of preference, it is actually a public law. Title 10 of the United States Code Section 2867 requires open protocol control systems in military construction. He further explained that he felt this was an unfortunate disconnect between Government and industry stating that the Government wants full and complete ownership of our systems, and industry wants to protect their proprietary elements that drive their technology and thus their business. This same sentiment was reflected in another interview with a senior USACE mechanical engineer by stating that VRF is a tool that you don't want to take off the table, but the Corps doesn't know how to deal with it yet.

5.4. Advantages of VRF Systems

Based on interviews with a variety of HVAC professionals and researching various publications for VRF systems, the perceived advantages mesh well with the advantages that are published. The items below were cited as advantages during interviews by more than one interviewee.

The most cited advantage was that these systems work very well for buildings with limited ceiling space. This element provides a huge benefit for the renovation of older buildings where space is often limited. The main foot print of the VRF mechanical system is made up of smaller refrigerant lines instead of larger ductwork. VRF systems require much less ceiling space than conventional systems because only the refrigerant piping and ducted outside ventilation air are accommodated. [12] As larger ductwork is not needed with this type of system to provide space conditioning, less ceiling space is needed, so there is the potential to reduce the height of a building which can save a substantial amount of money. Another benefit was that life cycle cost of VRF systems can often be lower as higher efficiencies than other systems may be achieved depending on the use of the building. Especially if a building allows for the heat recovery (simultaneous heating and cooling) feature to be used, this system will be extremely efficient. Potentially up to a 58% savings can be realized on energy costs [13] Occupancy satisfaction has a better chance of success due to better environmental controls and each office generally has a dedicated thermostat when using this type of system. Better environmental controls are provided from the variable capacity elements of this system versus other systems that may only have staged operations versus fully modulating operations. The system adjusts the flow of refrigerant to each indoor unit based on its operating conditions. It computes the amount of refrigerant required by each indoor unit and controls the refrigerant flow to ensure desired comfort level without over cooling or heating of the space. [14]

5.5. Disadvantages of VRF Systems

The most cited disadvantage was the need for very specific, detailed manufacturer based training for not only the long term maintenance of these systems, but also the initial installation of these systems. As previously mentioned, every vendor has their own proprietary control system that must be learned. Every manufacturer has their own unique way of executing this technology, and it is critical that the staff installing and maintain these systems receive extensive training. Training becomes even more crucial when you factor in that most HVACR manufacturers will not grant contractors permission to stock their systems, nor honour equipment warranties, unless installing contractors are properly trained and hold the necessary certifications. [15] Finding qualified or certified maintenance personnel must be a consideration when considering using these systems. Local parts availability must also be considered. A case study demonstrating the critical nature of this disadvantage is provided below.

The proprietary controls included in these systems is a major disadvantage as detailed above, but it is not just the controls that are proprietary in these systems. Each vendor has other proprietary components and the major components from one vendor are not compatible with other vendors. This element complicates both the design and procurement of these types of systems difficult as the Government cannot sole source the design to one particular vendor due to full and open procurement requirements. Designing a VRF system for competitive bid is challenging due to each manufacturer's unique implementation of the VRF system technology. Each has its own set of requirements and restrictions that must be considered. However, if the system is designed solely for a particular manufacturer's requirements, the design will be hard to bid by others. In particular, the capabilities of the proprietary central controls systems are vastly different. [16] One interviewee also expressed that the proprietary challenges of these systems can make it difficult to integrate these systems to a central monitoring system and to develop good test procedures

The risk of a large refrigerant leak is also a disadvantage. According to ASHRAE Standard 15, a VRF system is classified as a direct system/high-probability system where a refrigerant leak can potentially enter into the occupied space. [12] Standard 15, Safety Standard for Refrigerant Systems, strives to ensure a safe system by limiting the maximum quantity of refrigerant below that which is a danger to human occupants if a leak occurs. Manufacturers of VRF systems components advertise that 40 or more evaporators can be included on one piping network with more than 3,000 ft. (914 m) of refrigerant pipe. A traditional DX split system applied room-by-room has one condensing unit for each evaporator, with no interconnection to other split systems, and a refrigerant leak, therefore would discharge only that refrigerant contained in one individual split system. Because of the interconnecting refrigerant piping, a VRF system has the theoretical potential to discharge a much larger quantity of refrigerant to indoor spaces in a catastrophic leak occurrence. [3] UFC 3-410-01 further restricts the total refrigerant charge to 49 pounds or less.

Related to the refrigerant leak disadvantage is that with the large amount of refrigerant piping in the building, there will be a corresponding large number of refrigerant joints. Finding refrigerant leaks is much more difficult than finding water leaks as there is no visible evidence of the leak from a refrigerant leak as there is with water. Two interviewees had personally experienced major problems with leaks during the installation of VRF systems. One of these examples is provided as a case study below. Fortunately, these leaks occurred during construction, but if a leak occurs after a building is occupied, it could be a disaster as it will be even more difficult to find a leak once the building is full of people and furniture. A disadvantage unique to the Government is that many of these systems are manufacturers in foreign countries that can introduce a challenge to the Buy American procurement requirements for Government construction contracts. Another consideration for VRF systems is that a separate ventilation system must be provided as these systems are typically not ducted nor do they provide the capacity to handle the heavy latent load that can come with ventilation air for various parts of the world. Currently, ventilation systems used in conjunction with VRF systems are engineered on a case-by-case basis. Manufacturers are evaluating potential approaches for an integrated solution. [17]

5.6. VRF System Failure at Ft. Stewart, Georgia, USA

Ft. Stewart hired a contractor to build a child care center. This type of facility functions very similar to a "day care" facility in the private world but it can potentially be open 24 hours a day. A VRF system was installed in this building by a mechanical contractor that was not a local contractor. This contractor provided a VRF system that met all of the performance criteria in the contract, but they used one of the less prevalent VRF systems in the local market. The installation's maintenance staff were provided with minimal training for this system when the project was completed and turned over. As luck would have it, approximately two months after the one-year construction warranty had expired, the VRF system had a failure that resulted in the entire system being non-operational. The installation's maintenance staff attempted to diagnose the problem, but had not been provided adequate training, or the vendor's necessary proprietary software to allow them to further troubleshoot. The building had to be closed temporarily as they could not get the system back running. The building sat vacant for a while and ultimately was converted to be used for office space. The installation's maintenance staff reached out to all of the local service organizations but could not find anyone that was certified to work on this particular vendor's system. The maintenance staff ended up installing window air conditioning units in this building so that it could actually be used. During this time, one of the local service contractors received the proper factory training and software and was able to get the system running again. This case study clearly demonstrates one of the major drawbacks for VRF which is the need for specialized training for maintenance staff for these systems. Again, it is critical to have knowledge of not only the mechanical components of these systems, but also the proprietary control system and the associated software. Had adequate training and software been provided this situation could have been avoided.

5.7. VRF System Installation Difficulties at Ft. Benning, Georgia, USA

Ft. Benning had the need to convert a very old barracks building with very limited ceiling height into an office building. With the limited ceiling height, a VRF system was a very good option as there was not room for a large central duct system in the building and floor space was also extremely limited. The prime contractor hired an unqualified mechanical subcontractor for this project. This mechanical contractor had primarily done residential work prior to this project. This contractor had no prior experience with VRF systems and only received the factory training to install these systems since they were awarded this project. Only the owner of the company actually received the training, and the rest of the employees that worked for this company did not receive it. As the owner was managing other projects, the owner could not pay adequate attention to the installation details for this project that had a large amount of refrigerant piping connections. The prime contractor also did not have an adequate QC staff to watch over the installation of the system. When it came time to attempt to pressure test all of the piping, the contractor had an extremely hard time finding any sections of pipe that would hold pressure. They were going through bottle after bottle of nitrogen attempting to track down and repair all of the leaks in the piping system. Many of these connections were flared connections. Overall due to the number of leaks and the lack of effort by the contractor to find the leaks on a routine basis, it took over two months to find all of the leaks. Now the staff that oversaw the installation of this system has a fear that leaks will be a problem in the future for this project as the contractor hired laborers to repair these leaks that were clearly not diligent in their efforts for the initial installation or the prolonged effort to repair the leaks. This case study further demonstrates the need for proper, thorough training for the installation of these systems and also reinforces the concerns in the US Army Corps of Engineers design guidance concerning the desired types of connections for VRF system being a soldered or brazed connection.

6. Conclusion

VRF systems offer a variety of advantages and disadvantages that must be weighed when considering their use. This level of consideration applies to all projects, not just the Corps of Engineers. Most of the HVAC industry experts interviewed felt the same way when asked if the Corps of Engineers should use these systems. The response was almost universally that the Government should consider their use for limited situations, but especially for renovation projects with limited ceiling space as they are one of few viable options in this scenario. However, based on the current design guidance and interviews with senior engineers, there are currently too many risks to universally start using these systems, and the bottom line is that they do not meet public law as explained above so they cannot be used for military projects. The unique training requirements that must be learned for each manufacturer is a major drawback. As more and more companies develop these systems, that problem will continue to grow. The limited amount of maintenance personnel at military installations cannot possibly remember the details for every manufacturer of these systems to be able to adequately maintain and replace them. An installation will need to have access to a service contractor that is certified for each vendor that will be installed on their base. So, while the systems contain great advantages, the risks that come with those advantages are heavy especially if a major problem occurs with the system and adequate training was not provided to service personnel as is unfortunately common for military projects.

A private owner that has more purchasing flexibility for parts and service has a little less risk than the Government does due to procurement regulations for not only materials, but labor and services as well. So, if a project team is considering the use of this type of system, it is highly recommended that all stakeholders thoroughly evaluate all the advantages and disadvantages that are applicable to their situation to ensure that the life of the project will be a success if a VRF system is going to be considered. All team members including the designer, contractor, building owner, maintenance staff, procurement staff, building occupants must be allowed to weigh in on their particular experiences and concerns with these systems to ensure that the VRF system is a proper fit for their business. To minimize the risks associated with these systems, a building owner must make sure that only individuals that are highly experienced, qualified and certified by the *specific vendor* to be used are allowed to design, install, and maintain the system to be used on their facility.

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A Balanced Scorecard for Assessing Automation in Construction

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Abstract

Despite the economic importance of the construction industry worldwide, it suffers from low productivity compared to other sectors, due to weak industrialisation, fragmented supply chain and poor collaboration. Recent national initiatives are promoting the adoption of information and automation technologies to increase efficiency, quality, safety, and reduce costs in construction. Emerging technologies will also provide highly integrated, connected and scalable new methods of construction. Nevertheless, the benefits and risks of automation in construction remain largely unknown due to the lack of standards and management tools to assess them from a holistic perspective.
The aim of this research is to develop a Balanced Scorecard (BSC) as an evaluation framework for automation in construction. A BSC is a strategic management system that links performance measurement to business strategy using a holistic set of performance assessment criteria. BSCs expand evaluation beyond financial criteria to include environmental and social considerations. The proposed BSC under development in this research uses a hierarchic system of multidimensional indicators (e.g. resource consumption, GHG emissions, costs, productivity, etc.) relevant to automation in construction, at operational, organisational and societal levels. The validity, priority and accessibility of the indicators were explored via a workshop with 20 participants from the construction industry. The workshop outcomes provided a means to focus attention on relevant key performance indicators (KPIs) for decision-making regarding construction processes. Based on the outcomes of this study, the final BSC will help construction organisations to achieve their sustainability goals and address low productivity, because automation solutions can be seen through a holistic, and pragmatic lens, thus are more likely to be included in, and contribute to, construction operations in the future.

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Keywords: balanced scorecard; automation; construction; KPIs; sustainability, assessment.

1. Introduction

With annual revenues of nearly $10 trillion (6% of global GDP), the construction industry is of strategic importance to the world's economy [1]. Despite this, productivity in the construction sector in many countries has been stagnating in recent decades and it has not been able to keep pace with the increasing productivity in other sectors [2]. The causes for this are numerous and include factors such as an adversarial culture, resistance to introduce new technologies, low industrialisation of construction processes, fragmented supply chain, poor collaboration and data interoperability [3] [4]. As a result, some countries have launched government and industry initiatives to overcome the current problems in construction. Key initiatives, such as the "Construction 2025" strategy in the UK, aim to develop an efficient and technologically advanced industry through the investment in smart construction and digital design [5]. The

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digitalisation of the construction industry (referred as Construction 4.0) through the adoption of construction technologies such as Building Information Modelling (BIM) is already transforming the construction industry [6]. Over the next decade, BIM will be combined with other technologies such as the internet of things and robotic manufacturing. As a result, automated construction technologies will facilitate a highly integrated, connected and scalable construction process.

Automation in construction offers radically different ways of planning and constructing the built environment [7, 8], but this has implications for the environment, the economy and society. Understanding how automation can enhance productivity and efficiency in construction, while also ensuring a sustainable development, has the potential to improve performance of industrialised organisations in the round. However, evaluating automation in construction requires a well-defined and consistent framework. The aim of this research is to develop a Balanced Scorecard (BSC) to be used as an evaluation framework for automation in construction and to support the establishment of quantifiable measures and targets to improve the performance of organisations, through the balanced use of automation. This paper presents an initial set of Key Performance Indicators (KPIs) selected to evaluate automated construction processes from all sustainability dimensions. The validity and applicability of the proposed KPIs is tested and verified through a workshop with industry experts in construction and innovation. As a result, a model of BSC based on a hierarchic organisation of the indicators is proposed in this paper, which will later be verified and refined through further research phases, including the evaluation of a case study of automation in construction.

2. Automation in Construction

Although computer-controlled machines and robotic systems have started to be used in construction [9], the adoption of automation and robotic technologies in the building industry has remained a marginal phenomenon [8]. The notion of automation in construction is very broad, including systems from mechanical machinery manipulated by humans, including semi-automated devices with remote control, to autonomous robots with sensors and automated control features [10]. Skibniewski [11] defined construction automation as “the engineering or performance of any construction process, on-site or off-site, by means of teleoperated, numerically controlled, semiautonomous, or autonomous equipment”. Mahbub [12] defined construction automation as the use of self-control mechanical and electronic machinery with intelligent control mechanisms to conduct construction tasks and operations automatically. For this study, automation in construction will refer to the use of robotic systems to perform construction tasks, including technologies and applications on both ends of automatic-autonomous spectrum.

The first attempts to introduce robot-based processes in the construction industry took place in Japan during the 1990s. The implementation of robots in construction at that time focused on the development of single-task automated devices. Such machines were designed to improve productivity by automating a conventional construction process, such as bricklaying masonry, welding, concrete slab finishing, or paint spraying [13]. More advanced examples of robotic applications in construction were not seen until 2005, when ETH Zurich started to investigate the use of industrial robots for additive prefabrication of non-standard architecture [14]. Another pioneering example of automation in construction was the project Contour Crafting (CC), a concrete-extrusion fabrication process suitable for large-scale construction [15]. Over time, the ability of robotic systems has grown, extending the scope of experimentation beyond the factory towards on-site applications. Examples of mobile robotic systems that can be applied for additive building manufacturing include semi-autonomous industrial robotic arms [16] and multi-agent autonomous flying robots [17], as shown in Fig. 1

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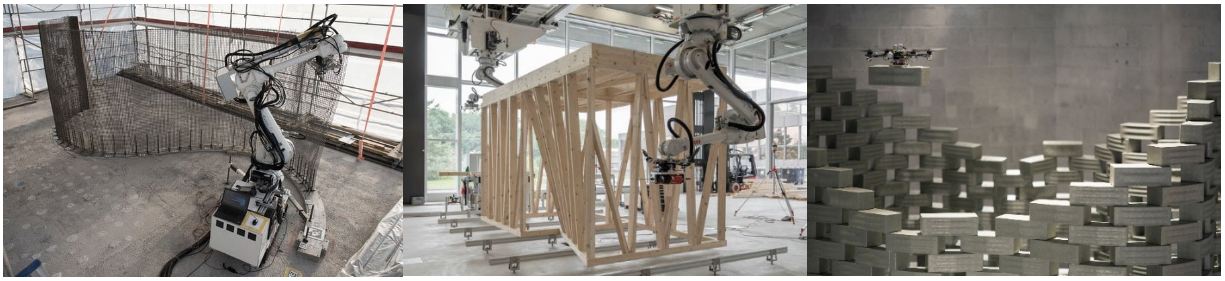

Fig. 1. Examples of automation in construction (Source: Gramazio Kohler Research, ETH Zurich [18]).

Despite the potential offered by the technology, there has been minimal research on the benefits that automation can provide to the construction sector. Initial research has explored the environmental, economic and social advantages of automation in construction, including quantification of sustainability benefits, highlighting material optimisation and functional integration [19], and the potential productivity benefits associated with the implementation of robotic systems [20]. Beyond these contributions, the performance of automated construction processes has not yet been investigated in a systematic manner and broader impacts remain largely unknown. Importantly, data uncertainty and a lack of management tools and standards in the area challenges the capacity of industrialised construction organisations to set goals, measure performance and manage changes to make their operations more sustainable.

As society becomes more aware of the activities and costs behind reported profits, companies have wider responsibilities than pursuing financial profits. Issues such as climate change, pollution, resource consumption, employment, health and safety, etc. have become highly relevant for organisations, including those in construction [21]. An increasing demand for sustainability has the potential to serve as the trigger for a large-scale deployment of automation in construction, so the construction industry needs guidance on systematic decision-making in this emergent domain. The few studies that have tried to deliver a comprehensive framework to evaluate automation in construction according to the three pillars of sustainability are far from real-world applications in an industrial context [10]. There is an urgent need for research to support the management of planning, construction and operation of building and infrastructure projects constructed with automated techniques. Understanding how these technologies can improve sustainability is essential to progress the digitalisation of the construction sector.

3. Methodology

3.1. Balanced Scorecard (BSC)

The need to report sustainability performance externally has led to a growing need to engage with sustainability issues and developments in data collection systems to integrate the social and environmental performance data into decision-making, risk management and performance management. Consequently, performance measurement approaches traditionally employed by organisations, such as budgeting and activity-based costing, have evolved into multi-dimensional performance measurement systems (PMS). PMS such as the Performance Pyramid, the Balanced Scorecard and the Performance Prism embrace a variety of financial and non-financial performance metrics to manage performance and strategic decision-making in organisations. Among PMS, Balanced Scorecards (BSCs) [22] have been applied in major building and infrastructure projects in the UK as a means to more effectively include a broader range of criteria, including sustainability, within project decision making. In this case, the BSCs expand the evaluation criteria beyond traditional indicators such as cost, time and quality to include themes related to safety, equality, environment and legacy, which support the main priorities of stakeholders. The main purpose is to ensure that environmental and social aspects are scored alongside economic, and other traditional out-turn measures, more equitably within procurement policy, embedding sustainability into business strategy.

The emergence of new digital and robotic technologies in construction requires the re-evaluation and re-engineering of business practices to successfully handle operational and organisational changes [23]. The adoption of a well-known and comprehensive performance management model such as the BSC for assessing automation provides a balanced and robust way of evaluating these new construction processes, but existing BSC examples do not account for automation, so a new variant is required. Such a BSC would increase the likelihood that stakeholders (e.g. construction managers) will treat innovative approaches more fairly and make use of them in decision-making on projects and organisational development.

3.2. Key Performance Indicators (KPIs)

A literature review and classification of existing and emerging automated construction technologies and processes guided the definition of the principal dimensions and KPIs applicable to automated construction projects. Relevant publications, such as De Schutter et al. [24], allowed the identification of relevant parameters to assess the performance of automated construction processes, such as productivity, changes in the cost structure and stakeholders, energy consumption, material production, carbon emissions, etc. Moreover, research studies focused on the development of frameworks of indicators for assessing automation in construction, e.g. Pan et al. [10], and literature related to the use of BSCs for sustainability evaluation, including Nicoletti Junior et al. [25], were reviewed. Based on this analysis, and with the goal of integrating sustainability within an automated construction process, Table 1, Table 2 and Table 3 respectively show the selected lists of indicators associated with the three dimensions of sustainability. The tables include qualitative and quantitative data required for assessing and optimising the performance of an automated construction process in relation to each indicator (e.g. costs, emissions, material use, energy demand, and employment). Each dimension presents the indicators in respect of three different levels: Operational (OP), Organisational (OR) and Societal (SO), where:

- OP indicators can be employed to evaluate performance of the construction process.
- OR indicators relate to how the automation adoption would influence performance of the organisation.
- SO indicators refer to the impact of automation on society.

Table 1. Environmental KPIs for assessing automation in construction.

Indicators	Assessment data
Material consumption (OP)	material composition, material type (virgin, recycled), material quantity (kg, m^3)
Waste production (OP)	waste composition, waste type (hazard, recyclable), waste quantity (kg, m^3)
Technology production (OP)	robot type, material composition, material type (virgin, recycled)
Energy consumption (OP)	energy type, technology power (W), construction time (hours)
GHG emissions (OP)	CO_2 (kg), CH_4 (kg), N_2O (kg)
Air pollution (OP)	SO_2 (kg), NO_x (kg), NMVOCs (kg), NH_3 (kg), PM_{10} (kg), $PM_{2.5}$ (kg)
Water use (OP)	water quantity (litres)
Environmental strategy (OR)	contribution to environmental goals
Environmental compliance (OR)	compliance with environmental legislation
Resource scarcity (SO)	use of rare materials (high, low)

Table 2. Economic KPIs for assessing automation in construction.

Indicators	Assessment data
Material cost (OP)	material cost (£)
Labour cost (OP)	number of employees, function, salary (£)
Technology cost (OP)	hardware cost (£), software cost (£)
Operational cost (OP)	energy cost (£), water cost (£), maintenance cost (£), license cost (£)
Waste management cost (OP)	disposal/recycling cost (£)
Productivity (OP)	construction cost (£), construction time (hours), project dimensions (m^3)

Quality (OP)	cost of rework (£), delay (hours)
Profitability (OR)	revenue (£), market share (%)
Competitiveness (OR)	new business opportunities, dividend (£)
Innovation (OR)	R&D (£), IP (£), training (£), technology acquisition or lease (£)
Community investment (SO)	amount given as % of earnings (£)

Table 3. Social KPIs for assessing automation in construction.

Indicators	Assessment data
Health & Safety (OP)	number of incidents/hour, number of fatalities, hazards exposure
Working conditions (OP)	work activity (physical, intellectual), training, salary and benefits
Workforce diversity (OP)	employees age, gender, race, disabilities
Ethics in supply chain (OR)	code of conduct (anti-corruption, human rights)
Social compliance (OR)	compliance with social legislation (health & safety, etc.)
Community benefits (SO)	employment increase (%)
Social acceptability (SO)	positive media coverage

3.3. KPIs validation in the industrial context

In order to explore and verify the validity and applicability of the above indicators for assessing automation in construction in the industrial context, a workshop was organised for construction industry stakeholders. In total, 20 experts in sustainability, innovation, project management, automation, and business strategy working within UK construction organisations were recruited to participate in the workshop. They were a mixed group drawn from major contractors, consulting engineers and manufacturing organisations, with expertise in design, computing, materials, and construction and project management. The workshop was designed to collect individual views and also encourage active debate among the participants, given the emergent nature of the subject area; the approach was exploratory and essentially qualitative in nature.

Initially, the participants were divided into five working groups, each with a balanced mix of organisation types and expertise. Then, the concept and implications of automation in construction were introduced showing examples of recent applications. Once the context was clear, the environmental, economic and social indicators in Tables 1-3 were explained. The participants were then asked to freely organise the indicators according to the following criteria in the context of their organisations:

- Prioritisation (from high to low): i.e. the relevance of each indicator in respect of assessing automated construction processes.
- Ease of data access (from easy to difficult): i.e. the ease with which data on a given indicator can be accessed, currently.

Furthermore, the groups had the option to add indicators to the KPIs list. Each group presented their indicator lists on flipcharts and there was a plenary discussion to share final thoughts about the subject.

4. Results

4.1. "Prioritisation" exercise

The results of the first workshop exercise showed that the priority of the KPIs varied between groups of stakeholders and different types of organisations. Looking at the indicators from a sustainability perspective, groups 1, 3 and 4 gave higher priority to economic and social indicators, preferring the economic indicators (see Fig. 2). In contrast, group 5 indicated that environmental indicators were more relevant and group 2 distributed the priority between environmental, economic and social indicators more equitably. Despite this variance, all the groups considered some KPIs to be equally important. On one hand, the economic indicators *Productivity* and *Profitability* were considered highly relevant for assessing automation in construction. Similarly, the social indicator *Health & Safety* was given high priority by all stakeholders, due to regulatory and legal requirements. These results showed that the main drivers of the construction industry remain financial, but the importance of social regulations is increasing in the sector. On the other hand, all stakeholders tended to award medium priority to environmental indicators such as *Material consumption, Energy consumption* and *Waste production* and low priority to *Technology production*. Environmental aspects are gaining relevance for construction stakeholders, but they are still considered essentially secondary when framed in an evaluation of an automated construction process.

Interestingly, looking at the KPIs from operational (OP), organisational (OR) and societal (SO) perspectives, prioritisations did not appear to be clearly related to these classification levels (see Fig. 2). However, the indicators corresponding to legal or regulatory requirements, such as *Environmental Compliance* and *Social Compliance*, were given high priority and most of them belong to the organisational level (OR).

Finally, all five groups highlighted the need for additional indicators. Among the KPIs proposed, groups 1, 2 and 5 suggested *Workforce skills and training*. The adoption of automation in construction will require workers to have digital skills and training of current employees will also be needed. The consideration and measurement of these issues in the BSC was clearly important for the workshop participants.

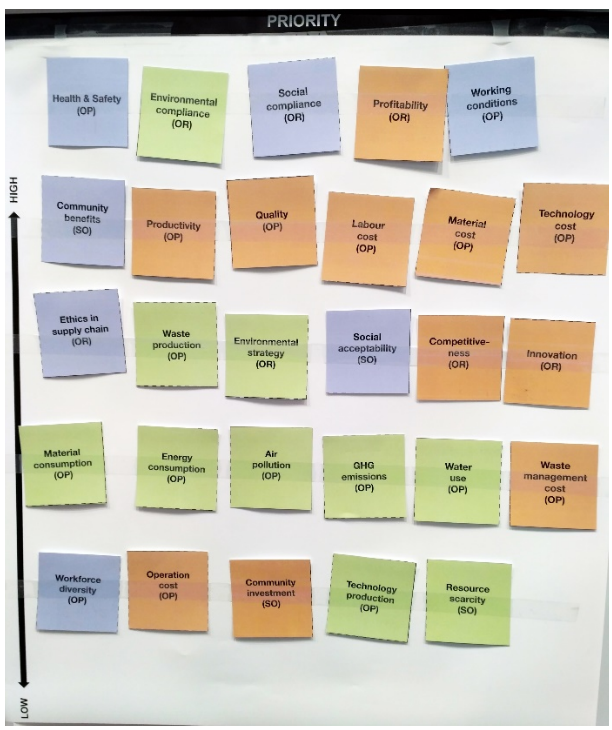

Fig. 2. Example of results from the "Prioritisation" exercise (Group 4).

4.2. "Ease of data access" exercise

The results of the second workshop exercise also showed that the ease of data access for assessing the KPIs varied between groups of stakeholders. Looking at the indicators from a sustainability perspective, only group 1 rated the economic indicators as having a much higher ease of data access, while the rest of the groups distributed environmental, economic and social indicators more evenly. Despite the variability between the groups, they all identified that data for certain KPIs was much easier to access, namely economic indicators (e.g. *Material cost* and *Labour cost*). These are well-known metrics commonly employed for assessing construction projects; all construction organisations have databases containing this type of data. In contrast, the social indicators (e.g. *Ethics in the supply chain* and *Workforce skills and training*) were considered rather more difficult to access and assess due to low data availability. Data related to parameters like working conditions, diversity, ethics are less frequently or consistently collected; they are often qualitative measures, indicating an important barrier to the inclusion and assessment of social indicators in a BSC.

Looking at the KPIs from an operational (OP), organisational (OR) and societal (SO) perspective, (unlike the prioritisation exercise) ease of data access does seem to be more closely related to these classification levels. For instance, the data required for evaluating operational indicators such as *Material consumption* or *Operational cost* were identified as easier to access than data concerning societal indicators such as *Community benefits* and *Social acceptability*. This result highlights the relevance of scale and scope when assessing the impact of automation in construction. For instance, the stakeholders clearly considered that it would be easier to measure the effects of automation on the construction process than measuring its impact on society.

5. Proposed model for the BSC

Based on the results of the workshop, an initial model for the Balanced Scorecard was developed, which offers an innovative method for assessing the performance of automation and robotics in the sustainability context. Fig. 3 shows the proposed model, which includes environmental indicators (green), economic indicators (orange) and social indicators (blue) distributed along two axis: priority and data access. From the list of KPIs presented in Tables 1, 2 and 3, this model contains only those indicators that were rated consistently by the workshop participants. These indicative relationships will be used to inform the development of the final BSC.

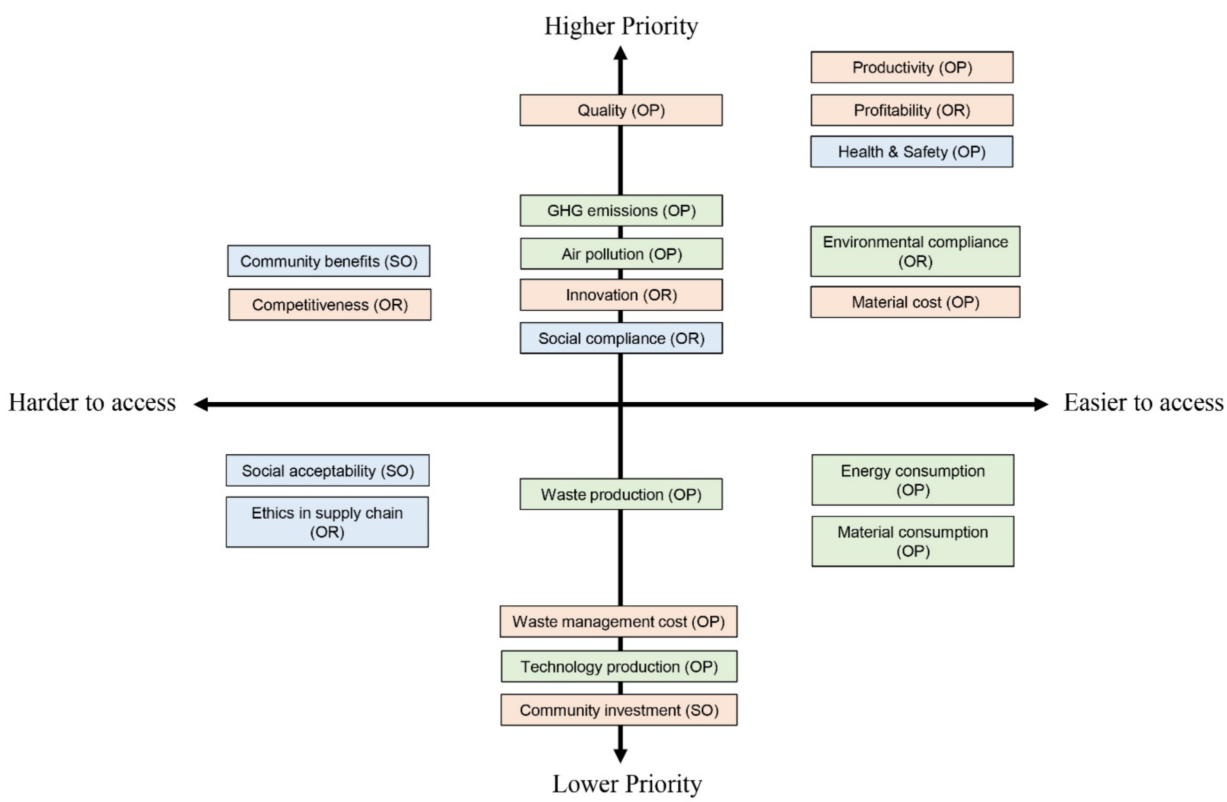

Fig. 3. Preliminary model for the Balanced Scorecard for assessing automation in construction.

Overall, Fig. 3 shows that there is no clear prioritisation of environmental, economic or social indicators (as discrete groups), neither is there any clear prioritisation of operational (OP), organisational (OR) or societal indicators. The KPIs are distributed equitably along the priority axis, nevertheless the model shows that traditional out-turn measures tend to dominate thinking among the workshop participants. Therefore, there is a clear relation between this framework for evaluating automation in construction and traditional PMS for assessing current processes in construction. The model also shows that the priority and ease of access for indicators related to compliance of regulations is intermediate and social indicators (e.g. *Ethics in the supply chain*) tend to be deemed lower priority and harder to access.

Looking at the indicators in more detail, *Material cost* is given a higher priority than *Material consumption* and *Waste production*. This indicates that economic measures are still preferred over environmental measures to evaluate the performance of construction processes. Finally, among environmental indicators, GHG emissions is prioritised over energy consumption, although the latter is easier to access. Clearly the priority is not always influenced by data access and it may depend on how relevant is the indicator for the specific industry, in this case construction.

Based on the observations from Fig. 3, the final BSC should hierarchically organise KPIs in three generic groupings from high to low priority: Out-turn measures, Compliance measures, and Target measures (to be classified more precisely in the next stage of the research). This classification differs from previous models of BSC presented in the literature. In the original BSC model, Kaplan and Norton [22] organised measures in four perspectives: financial, customer, internal business process, and learning and growth. Later publications such as Möller and Schaltegger [26] and Nicoletti Junior et al. [25] adapted the traditional BSC management perspectives to include indicators relevant for sustainability evaluation. More recent BSC models used for the procurement of large infrastructure projects in the UK [27] have challenged the traditional BSC structure by classifying KPIs in key strategic themes that represented policy areas relevant to the objectives and requirements of the project (i.e. solution quality, costs, supply chain, employment & skills, environmental sustainability, health & safety and outcome benefits). In line with these project-based models, the outcome of this research will provide a BSC adapted to the needs of new automated construction processes, and which is sensitive to its industry setting. The classification of indicators in three categories will prioritise essential issues to improve the performance of organisations.

6. Conclusion and Outlook

Shortcomings in the construction industry have stimulated researchers and practitioners to search for new methods of increasing productivity and improving value. The adoption of greater automation offers potential, but as yet market adoption has been somewhat marginal and essentially experimental in nature. One problem is that the adoption of automation in construction requires frameworks and standards that support and guide management decisions in tune with global sustainability development trends.

The research presented in this paper is the first step to develop a robust evaluation framework for assessing automation in construction. The proposed Balanced Scorecard (BSC) model uses a hierarchic set of KPIs, which provide a holistic understanding of the impact of automated construction processes and facilitates a new pathway for achieving sustainability in buildings. The development of the BSC based on 20 industry stakeholders' views has confirmed the applicability of the framework for assessing the performance of automated and robotic construction processes in the industrial context. The workshop has also established that out-turn measures dominate thinking, followed by compliance-related issues.

Noting that the study is at an early stage of development, the research will continue and move towards a complete and reliable holistic assessment tool for real-world evaluation of automation in construction, in collaboration with construction companies. Beyond this study, the assessment of a case study of swarm-based robotic construction will be used to verify the BSC model, enhance its quality and utilise simulation data to test its effectiveness. The aim of the final BSC is to provide a realistic vision of the impact of automation and facilitate its implementation in construction to improve productivity, while ensuring the well-being of the environment and society.

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A Framework for Lean Construction Supply Chain; Bibliometric Analysis Approach

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Abstract

Lean construction supply chain is a project management technique adopted from the manufacturing sector aimed at improving the performance of the construction industry. However, it's implementation is confronted with some barriers in the construction industry such as; poor understanding of lean concept and absence of framework explaining the application. Therefore, this study developed a framework for lean construction supply chain adopting a bibliometric analysis approach. Bibliometric analysis is a statistical analysis of articles for revealing the school of thought, issues and problems in an area of study. The articles adopted for the analysis of this study were extracted from Scopus, Google Scholar and other online databases. The retrieved articles were inputted into VOS viewer software to reveal the network analysis. The analysis showed the significant countries and school of thought supporting the lean construction supply chain. The findings from the analysis showed that the construction industry in most African countries is slow towards the adoption of the lean concept. The network analysis showed that the practice of lean construction supply chain revolves around waste reduction, just in time, integration and pre-fabrication. This practice formed the variables used for developing the framework. The study recommends that further research should be conducted to validate the framework developed from the study. The study contributes to improving the practice of lean thinking within the construction industry.

Keywords: Bibliometric analysis; Construction supply chain; Lean thinking; Lean construction.

1. Introduction

Balaji and Senthil Kumar [1] indicated that lean thinking is a management concept adopted from the manufacturing industry. The idea originated from the manufacturing of Toyota cars that were designed by engineer Ohno. According to Koskela, et al. [2], the term "lean" was developed by a research group conducting research on cars production to reflect the nature of waste reduction adopted by Toyota manufacturing in comparison with mass car production system. The comparison was made with Ford cars that made mass production system. But Ohno aimed at delivering cars to meet customer demand. The idea was to eliminate waste through shifting focus from the activity to the overall delivery system. Ohno perceived waste as the failure to meet the specific requirement of a customer with zero inventory [2]. It

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is reasonable to envisage that lean thinking was used in the manufacturing sector for waste reduction with a view to adding value to clients.

The inherent waste experienced in construction sites made lean thinking suitable for the construction industry [3]. Although Saurin [4] stipulated that the construction industry has rejected multiple ideas from the manufacturing sector but lean fits into the agenda of the industry. For instance, delivering a project to meet the client's needs while eliminating waste and the unnecessary cost is the goal of every construction project manager. Yunus, et al. [5] asserted that construction waste occurs due to activity centre thinking of construction professionals, therefore, an idea that supports change in thinking will be appropriate for the industry. Murata, et al. [6] asserted that applying lean thinking will improve the management of construction projects.

The adoption of lean thinking for managing construction project activities was referred to as lean construction supply chain in this study. Jung [7] submitted that construction supply chain management is complex when compared to other sectors due to the project-based nature of the industry. Also, Meng [8] specified that the complexity of the construction supply chain is enormous due to the numerous dissimilar consultants. The consultant includes; designers, suppliers and many others who come together to work on a short-term basis for a project with this organisation having their supply chains. Mandeep, et al. [9] discovered that the complexity of the construction supply chain can be revealed in its structure as it contains a minimum of 3 tiers. The tiers have each specific functions assigned to them the first tier is responsible for preparing the project. The second undertakes the managerial activity during the project construction phase and the last tier is responsible for supplying the materials needed for the construction project. This implies that managing the construction supply chain can be broken down into numerous process and activities.

The management of the construction process can either be driven by a pull or push system [8]. In the push system, the construction project is planned, controlled and delivered without any regards to the customers' needs and wants with the assumptions that all construction projects (housing) will be disposed or sold on the market. However, as time changes coupled with high competition, the push system became outdated and it moved towards the pull system. This system is characterised by construction production triggered by the customers thereby requiring on-time delivery of construction project, integration of construction project team members and many others. The change to the pull system in the construction industry leads to the adoption of lean thinking as a project management technique for meeting client needs at a reduced cost [2].

The application of lean within the construction industry has attracted numerous research such as; [10-12] but most of the research is focused on hinderance, benefits for implementing lean construction. However, there is a lack of research regarding the school of thought supporting the lean construction supply chain. The understanding for the school of thought is significant because to implement lean thinking for CSC fully it requires the proper knowledge of the underlying concepts. Also, the school of taught or knowledge base will provide the opportunity for developing a framework for the lean construction supply chain.

2. Methodology

The methodology adopted by this study is the review of existing literature related to the subject topic (lean thinking and construction supply chain). The literature was retrieved from Scopus database, Google Scholar, Web of science and other databases like Emerald and Jstor. The literature was searched online using keywords such as "Lean thinking" "lean production" "lean construction" "lean supply chain" "construction supply chain management techniques" and "lean construction supply chain". Through using these keywords, initial literature of 12,583 was retrieved from the database. A review of the literature shows that the majority of them concentrated on lean within the manufacturing sector. To further refine the articles "lean construction" was inputted into the search within the bar and it produced a total of 2,038 articles. However, since the aim of the research is focused on construction supply chain lean construction supply chain was inputted, and it produced a total of 850 articles. Therefore, a total of eight hundred and fifty literature were extracted and used for the analysis.

The articles were analysed with VOS viewer software to provide the citation, co-citation, journals and author analysis. The citation and journal analysis assist in revealing the essential authors and journals that have contributed significantly to the development of lean construction supply chain. The important authors were ranked based on their total strength link that represents the connectivity of the authors to other authors within the subject area. The important articles were further subjected to content analysis of the literature review to reveal the school of thought guiding lean CSC. Whereas co-citation provides the understanding of the external impact of citations on a subject matter. van Eck and Waltman [13] affirmed that co-citation analysis comes in various format author citation, journal citation and sources citation. This study adopted author co-citation because it believes that authors that are co-cited in literature imply that they conduct literature in a similar research area.

3. Analysis of literature

The analysis of the literature extracted from the database is presented in this section. The analysis reveals the countries and authors that contribute mostly to lean construction supply chain. Also revealed are the significant school of thought related to lean construction supply chain. The school of thought were used to develop the framework for this study.

3.1 countries contributing to lean construction supply chain publication

The top countries contributing to a lean construction supply chain are presented in Table 1. A look at the table shows that the countries are ranked according to their total link strength. The Vos viewer software produces the total strength link and it functions as a standard for weighing an attribute [13]. Also, the weight of an item also represents the level of importance given to such item. The countries were ranked based on the highest number of total strength link. Therefore, the country with the highest number of total strength link represents the most important country concerning the publication of lean construction supply chain.

Table 1. countries contributing to lean construction supply chain

Country	documents	citations	total link strength	Rank
United Kingdom	107	2623	305	1
United States	155	2353	240	2
India	68	1190	159	3
Brazil	64	561	90	4
Sweden	33	387	76	5
Israel	13	346	62	6
Canada	28	515	58	7
Malaysia	28	224	58	8
Australia	27	460	53	9
Denmark	13	324	50	10
Germany	28	197	48	11
Italy	25	257	46	12
Hong Kong	13	112	41	13
China	24	180	38	14
Finland	23	304	38	15
Singapore	16	200	38	16
Norway	21	107	36	17
Spain	14	384	36	18
New Zealand	22	116	30	19
Iran	11	120	28	20
United Arab Emirates	10	152	20	21

Chile	25	269	15	22
South Korea	13	23	15	23
Netherlands	12	213	11	24
Portugal	11	60	7	25

Table 1 shows that the top countries responsible for publishing lean construction supply chains are; United Kingdom, United States, India, Brazil, Sweden, Isreal, Canada, and Malaysia. This implies that sufficient articles related to the lean construction supply chain can be found in the database of the countries aforementioned. It can also be deduced that the countries efficiently adopt lean construction supply chain.

3.2 Influential authors

Another strength of the bibliometric analysis is the ability to identify prominent scholars within a field of study. Table 2 presents the list of prominent authors, and it shows the number of articles including the Scopus citations of each author. A cursory look at the table revealed that all the authors have a minimum of 5 articles that are index in Scopus with a minimum number of 0 citations in Scopus. The total link strength of the authors is presented in the third column which shows the overall strength of the authors within the lean construction supply chain. The total link strength represents the connectivity of the authors to other authors within the subject area, therefore, their level of influence was ranked based on that.

Table 2. Influential authors

Author	Number of articles published	citations	Total link strength	Rank
Koskela, l.	31	422	57	1
Tezel, A.	13	36	49	2
Aziz z.	7	19	26	3
Tzortzopoulos p.	8	18	25	4
Saurin T.A.	10	186	22	5
Matt, D.T.	7	51	21	6
Rauch, E.	7	38	21	7
Sacks, R.	12	339	21	8
Dallasega, P.	7	26	20	9
Pasquire, C.	14	137	18	10
Ballard, G.	20	347	17	11
Marodin, G.A.	5	154	15	12
Tommelein, I.D.	12	259	14	13
Al-hussein, M.	10	152	10	14
Emuze, F.	5	0	2	15
González, V.	8	87	2	16
González, V.A.	5	22	2	17
Bulhões, I.R.	6	24	1	18
Lidelöw, H.	5	7	0	19
Stehn, I.	5	102	0	20
Formoso, C.T.	11	63	10	21

Table 2 shows that the topmost authors are Koskela with 31 Scopus document, 422 citations and a strength link of 43. Other influential authors are Tezel, Aziz, Tzortzopoulos, Saurin, Matt, and Rauch. A further investigation into this authors reveals that they are from developed countries like Germany, United Kingdom, United States of America and Australia. Whereas authors with low total link strength like Emuze are from Africa, this represents the poor adoption of lean thinking within the Africa context.

3.3 Framework and School of thoughts for lean construction supply chain

This study adopts co-citation analysis to reveal the intellectual structure or school of thoughts underlying lean construction supply chain. The findings from the school of thoughts were used to develop the framework used for this study. This study adopted the author co-citation analysis that visualizes the similarities in the scholarship of authors. Zupic and Čater [14] opined that co-author citations analysis presents a network diagram showing the structure of the knowledge base and different author's school of thoughts. Figure 1 presents the author co-citation analysis map calculated by VOSviewer software. The co-citation map shows the nodes that represent different authors. The size of the nodes depicts the number of co-citations of the author while the author with the biggest node indicates the number of times the author has been cited. A look at the map reveals that the authors are grouped into different coloured clusters that serves as the school of thoughts for each author. Figure 1 shows that the author is grouped into four colours namely; blue, green, yellow and red and it represents the school of thought surrounding lean construction supply chain.

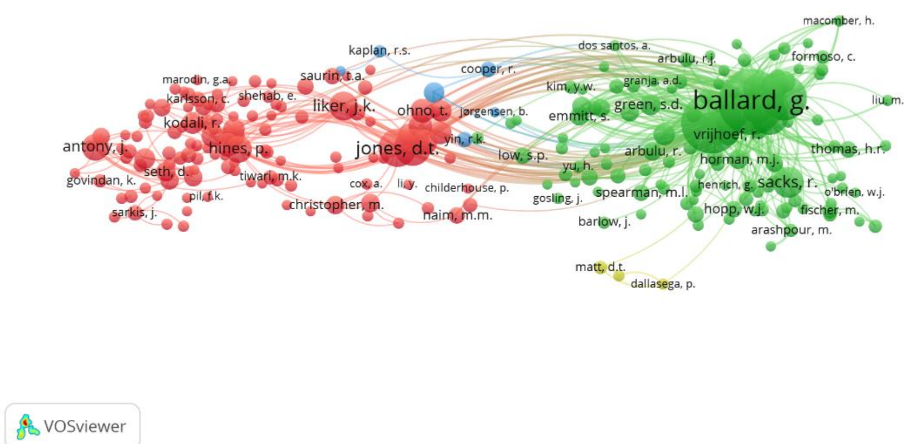

Fig. 1. Co-citation analysis

In support of the co-author citation, a content analysis was conducted to review the articles published by the authors. The finding from the analysis reveals that the school of thought can be broken down into waste reduction, Just in time, Integration and prefabrication. The first school of thought depicted by colour green perceived that the major aim of the lean construction supply chain is targeted at waste reduction. The leaders in this school of thought are [2, 10, 15] depicted by the large nodes in figure 2. The authors in this category modelled waste in the construction according to Engineer Ohno of Toyota production. They revealed that waste in construction occurs due to the concentration on each activity of construction project alone. Whereas a majority of the waste is experienced at the construction stage due to inadequate information, poor design and weak integration of construction activities.

The second school of thought is depicted by the colour red, and it is dominated by authors such as [4, 16, 17]. Authors in this school of thought recognise waste as the main core of lean construction supply chain but they believe that waste cannot be eliminated without the integration of construction activities. The third school of thought is depicted by colour yellow, and it is championed by [18-20]. According to this school of thought, engineering to order

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or prefabrication must be put in place to ensure effective lean construction of supply chain. The fourth school of thought is presented by colour blue from the review of articles published in this category believed that for effective lean construction Just in time techniques must be put in place.

waste reduction, Just in time, Integration and prefabrication

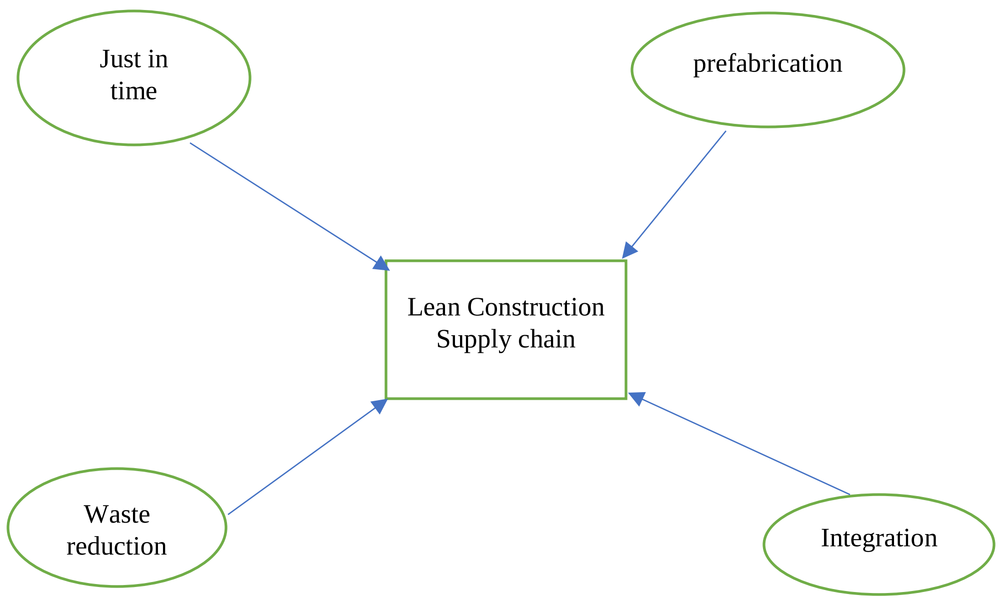

Fig 2. Lean construction supply chain framework

Figure 2 provides the framework for lean construction supply chain for the construction industry. The framework shows that waste reduction, integration just in time and prefabrication are the variables supporting lean construction**.**

4. Conclusion

The construction industry is responsible for providing the infrastructures needed for the development of any country. Unfortunately, the construction project management techniques used for producing the infrastructures are characterised with numerous shortcomings causing project delays and wastage. These shortcomings made the industry adopted lean thinking for managing the construction supply chain. Lean thinking is a concept that has strived successfully in the manufacturing sector and is presently utilized within the construction industry.

Towards improving the practice of lean thinking for managing construction supply chain this study conducted a bibliometric analysis of its knowledge base within the construction industry. It concludes that lean thinking for managing construction supply chain is effectively adopted within the construction industry but is implementation in Africa is low judging from a few research conducted in the study area. The primary school of thought supporting lean construction supply chain includes waste reduction, just in time, integration and pre-fabrication. Therefore, a framework was developed using the variables from the school of thought. The study recommends that further research should be conducted on validating the framework based on the school of thought extracted from the analysis of the journals

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A Multi Objective Scheduling Model for Minimization of Construction Project Duration, Total Cost and Environmental Impact

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Abstract

The performance of construction projects has traditionally been measured based on cost, time, and quality. Recently, the environment impact has been introduced as a fourth criterion for the assessment of project performance. Significant research advancements have been made in the area of optimizing resource utilization to minimize the total cost, duration, and quality for construction projects. A number of models have been developed using a variety of methods, including heuristics methods, mathematical programming, genetic algorithms, ant colony, and particle swarm optimization. However, there has been little or no reported research focusing on studying and optimizing the collective impact of resource utilization decisions on construction cost, duration, and environmental impact. The objective of this paper is to present the development of a multi-objective optimization model for optimizing resource utilization and scheduling of projects. The model provides construction planners and decision makers with new and important capabilities, including: (1) evaluating the combined impact of multiple resource utilization decisions on construction cost, duration, and environmental impact and (2) generating and visualizing optimal/near-optimal resource utilization and scheduling plans that provide optimal trade-offs between the project cost, duration, and environmental impact. The model is developed in two stages: (1) model formulation to identify the decision variables and optimization objectives for the construction optimization problem and (2) model implementation to perform the optimization computations using three modules that compute project duration, total cost, and environmental impact, respectively.

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Keywords: Multi objective optimization, Environmental impact, ;

1. Introduction

The construction industry, which has a major share in consuming natural resources and energy, will continue to impact the physical environment as long as the industry demands natural resources. The construction and demolition processes cause several direct and indirect environmental impacts. These impacts are serious and need to be controlled. Current construction methods involve consumption of a large amount of energy that directly impacts environmental impacts through both fuel extraction and supply. Moreover, the emissions generated to produce this energy produce hazardous gases as well as dust and noise pollution. Thus, the impact of construction projects on the environment requires the assessment of the contribution by each activity. Therefore, it has propelled many construction professionals to consider

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environmental impact as a performance assessment of construction projects [1]. Environmental impact was considered as a performance assessment factor for construction projects. Various studies have addressed environmental impact model for building during the phases of design, operations, construction etc. Assessing contractors environmental performance through calculating an environmental performance score [2], qualitative analysis and quantitative assessments through measuring the construction pollution index [3]. Environmental impact by life cycle assessment approach [4].

The performance of construction project has traditionally been measured based on cost, time and quality. Recently, the environment impact has been introduced as a fourth criteria for the assessment of project performance. Significant research advancements have been made in the area of optimizing resource utilization to minimize the total cost, duration, and quality for construction projects. A number of models have been developed using a variety of methods, including heuristics methods, mathematical programming, genetic algorithms, ant colony, and particle swarm optimization. While these research studies have provided significant contributions to this important research area, there has been little or no reported research focusing on studying and optimizing the collective impact of resource utilization decisions on construction cost, duration, and environmental impact. The objective of this paper is to present the development of a multi-objective optimization model for optimizing resource utilization and scheduling of projects. The model provides construction planners and decision makers with new and important capabilities, including: (1) evaluating the combined impact of multiple resource utilization decisions on construction cost, duration, and environmental impact and (2) generating and visualizing optimal/near-optimal resource utilization and scheduling plans that provide optimal trade-offs between the project cost, duration, and environmental impact. The model is developed in two stages: (1) model formulation to identify the decision variables and optimization objectives for the construction optimization problem and (2) model implementation to perform the optimization computations using three modules that compute project duration, total cost, and environmental impact, respectively.

This paper creates an automated way to choose optimum durations for the individual activities to maximize the benefits in time, cost, and effect on the environment. The research aims at achieving this in a user-friendly way that allows the owner to set his priorities. Sometimes time is the number one priority. For example, if you are building a structure or facility to be ready by a strict deadline like a stadium for World Cup or an exhibition hall for an international event. In this case, we need to focus on finishing the project on time no matter what the cost may be. In other projects, a residential compound or office building for example; while finishing on time is important but staying within budget may be the number one criterion. Minimizing the pollution may be more important than both time and money in other cases. The user has to rank his priorities to achieve minimum project time, least cost, or least Pollution; although the program would help in all three criteria.

However, there are limited studies on collective impact considering the multi objective nature of a construction project. This paper provides construction professionals with a model to evaluate the collective impact and generate optimal resource utilization and scheduling plans.

2. Environmental pollution impact measures and metrics

This task will focus on estimating and quantifying the environmental pollution impacts on the scheduling of construction projects. The pollution hazards such as noise, solid and liquid wastes, dust and harmful gases that are generated from construction sites represents serious environmental issues, in the present and future where the construction activities are increasing at very high speed. The awareness of these environmental issues should be addressed by all the government, construction companies and general public. There should be general consensus as to reduce the level of environmental pollution and hazard in construction projects especially in heavily populated urban areas.

The pollution generated by construction projects can be quantified by using two parameters, namely the Activity Pollution Index (API) and the Hazard Magnitude Index (HMI) [5]. The activity pollution Index (API) for activity n using crew formation C_n can be computed using the following equation:

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$$\boldsymbol{AEI(n, C_n) = \sum_{i=1}^{M_n} h(i, C_n) * D(i, C_n)} \tag{1}$$

Where $\boldsymbol{AEI(n,C_n)}$ = Environmental Index for activity $\boldsymbol{n}$ using crew formation $\mathbf{C_n}$, $\boldsymbol{h(i, C_n)}$ = construction hazard magnitude per unit time generated by a specific construction operation $\boldsymbol{i}$ for activity $\boldsymbol{n}$ using crew formation $\boldsymbol{C_n}$, $\boldsymbol{D(i,C_n)}$ = duration of construction operation $\boldsymbol{i}$ for activity $\boldsymbol{n}$ using crew formation $\boldsymbol{C_n}$ that generates hazard $\boldsymbol{h(i,C_n)}$, and $\boldsymbol{M_n}$ = number of construction operations for activity $\boldsymbol{n}$. The value of $\boldsymbol{h(i,C_n)}$ lies between zero and one indicating the seriousness of the hazard. For example, if a construction operation $\boldsymbol{i}$ for activity $\boldsymbol{n}$ using crew formation $\boldsymbol{C_n}$ generates noise that exceeds the threshold of pain, which is 140 db [6], then the value of $\boldsymbol{h(i,C_n)}$ is one. A value of zero is an indication that no hazard is generated by the construction operation.

3. Decision variables

The primary purpose of this development stage is to formulate a robust optimization model that supports both time and environmental index minimization. To this end, the present model is formulated to determine the main decision variables in this optimization problem and model the three important objectives of optimizing construction time, total cost, and environmental pollution impact in a robust optimization model.

For each construction activity in the project, the present model is designed to consider all relevant decision variables that may have an impact on project time and environmental index, including: 1) subcontracting option, which indicates whether the construction activity is performed using the contractor's own force or subcontracted; 2) construction methods, which represents the availability of different types of materials and/or methods that can be used; 3) crew configurations and sizes that represents the possibility of using single or multiple crews on each activity as well as the size of the used crew and/or equipment; and 4) crew overtime policy, which represents available overtime hours and night time shifts. To control the complexity of the optimization model, the present model combines these four major decision variables into a single variable called crew formation.

The major challenge confronting construction planners in this problem is to select an optimal crew formation option, from the available set of feasible alternatives (n=1…N), for each activity (i=1…l) in the project. The possible combinations of these alternatives create a large search space, where each solution in this space represents a possible resource utilization option for delivering the project. For example, a small-size project that includes 20 activities and five possible crew formations for each activity creates a search space of approximately 95 trillion (i.e., 5^{20}) possible solutions and this search space increases exponentially with the increase in the number of activities in the project. The present model is designed to help planners in this challenging task of searching large solution spaces to identify optimal crew formation plans that achieve multiple project objectives. The two main objectives in the present model are to 1) minimize the project overall time T; 2) minimize the project total cost, and 3) minimize environmental pollution impact.

4. Model formulation

The model will enable decision- makers to study the impact of various crew formation options on the project objectives in order to identify an optimal/near-optimal crew formation for each project activity. The impact of various crew formation decisions on activity cost, duration, and environmental pollution index need to be quantified and measured in order to minimize the overall project duration, total cost, and environmental pollution impact.

The project overall time T is computed using the following equation:

$$T = \sum_{n \in S_n} AD(n, C_n) \tag{2}$$

Where, $\boldsymbol{AD(n,C_n)}$ = duration of activity n using crew formation $\boldsymbol{C_n}$ and $\boldsymbol{S_n}$= set of critical activities. On the other hand, the project total cost ***TCost*** is computed using the following equation:

$$TCost = DirectCost + IndirectCost = \sum_{n=1}^{NA} AC(n, C_n) + a_0 + a_1.T \quad (3)$$

Where ***N*** = number of project activities, ***AC(n,Cₙ)*** = direct cost of activity ***n*** using crew formation ***C_n***, ***a_0*** = initial indirect (mobilization) cost, and ***a_1*** = indirect cost slope.

The project environmental index ***PEI*** is computed using the following equation:

$$PEI = \sum_{n=1}^{NA} AEI(n, C_n) \quad (4)$$

Where: ***$AEI(n,C_n)$*** = environmental index for activity ***n*** using crew formation ***C_n***.

5. Optimization module

The objective of this module is to search for optimal/near-optimal trade-offs between project time, total cost, and environmental pollution index using a multi-objective genetic algorithm model. Genetic algorithms are search and optimization tools that assist decision makers in identifying optimal or near-optimal solutions for problems with large search spaces. They are inspired by the mechanics of evolution and they adopt the survival of the fittest and the structured exchange of genetic materials among population members over successive generations as a basic mechanism for the search process (Goldberg 1989). The present model is implemented in three major phases: 1) initialization phase that generates an initial set of S possible solutions for the problem; 2) fitness evaluation phase that calculates the time, total cost, and environmental pollution index of each generated solution; and 3) population generation phase that seeks to improve the fitness of solutions over successive generations. The detailed computation procedure in these three phases is explained in the following sections.

5.1. Initialization

This step generates the random set of possible solutions. Parameters such as population size, generations, mutation rate and crossover mutation rate are read by the module. The project parameters are the number of activities, the number of crew formations for each activity, the duration and cost for each crew formation, and the predecessor activities. The initial population of binary strings is created randomly.

5.2. Fitness evaluation

The solution strings and each candidate solution are tested in its environment. The main purpose of this is to evaluate the time, cost and environmental index for each possible solution s in generation G to determine the fitness of the solution. This phase is carried out in two stages. All the solutions are assigned an identical dummy fitness. The lonely solutions are emphasized in the crow by sharing function strategy proposed by Deb 2001. Later all solutions are assigned fitness equal to the population size. This results in a fitness that any solution can have in any population. Therefore it calculates the project time, cost and environmental index for solution s in generation G.

5.3. Population generation

The purpose of this phase is to reproduce population according to the dummy fitness values. Three types of population are created parents, child and combined. A parent population is used to generate a child population. The child population is combined with the parent population to create the combined population. A new child population is created using genetic algorithm operation of selection, crossover and mutation. Selection operation which selects the solutions that can go through the process of reproduction, one with the higher shared fitness are favoured. Crossover operation which selected solutions are crossed at a randomly determined point and swap the variables in the strings at this point resulting in two new solutions. Mutation operation, in this operation the value of one of the variables in the string randomly changes to induce innovation and to prevent premature convergence to local optimal solution.
These all steps are continued until the number of generations is completed.

6. APPLICATION OF AN EXAMPLE

This study analyzes a construction project case to demonstrate the module to find an optimal scheduling solution for the project. The case project adopts the previously studied example of an actual tunnel construction project [9]. It comprises set of activities which have various possible crew formations. Each alternative is associated with a certain duration, cost, and pollution index. The activities considered in the example have several crew formations. Table 1 lists the duration, cost and environmental index for each activity crew formation.

Table 1. List of activities.

ID	Activity	Crew	ID	Activity	Crew
1	Excavation (1st part)	1	20	40 000	0.8
		2	18	50 400	0.9
		3	15	54 000	0.9
		4	14	58 800	1.0
2	Excavation (2nd part)	1	15	30 000	0.8
		2	12	34 000	0.8
		3	10	36 000	0.9
3	Sheet piles (1st part)	1	7	25 400	0.7
		2	5	29 000	0.9
		3	4	31 000	0.9
4	Sheet piles (2nd part)	1	5	19 000	0.7
		2	3	24 000	0.9
5	Dewatering	1	14	15 000	0.2
6	Water tightness (1st part)	1	3	20 000	0.2
		2	1	20 800	0.2
7	Water tightness (2nd part)	1	2	16 000	0.2
		2	1	16 400	0.2
8	Reinforcement for raft (1st part)	1	3	38 000	0.2
		2	2	39 000	0.2
		3	1	39 400	0.2
9	Reinforcement for raft (2nd part)	1	2	35 400	0.2
		2	1	36 000	0.2
10	RC for raft (2nd part)	1	1	24 000	0.8
11	RC for raft (1st part)	1	1	28 000	0.8
12	Formwork for walls (1st part)	1	5	8000	0.2
		2	3	9000	0.2
		3	2	10 000	0.2
13	Formwork for walls (2nd part)	1	3	7000	0.2
		2	2	8000	0.2
14	Reinforcement for walls (2nd part)	1	5	70 000	0.2
		2	3	72 000	0.2

		3	2	75 000	0.2
15	Reinforcement for walls (1st part)	1	7	76 000	0.2
		2	5	77 200	0.2
		3	3	77 600	0.2
		4	2	78 000	0.2
16	RC for walls (1st part)	1	4	50 000	0.8
		2	3	55 000	0.8
		3	2	60 000	0.8
17	RC for walls (2nd part)	1	3	40 000	0.8
		2	2	45 000	0.8
18	Formwork for slab (2nd part)	1	8	6000	0.2
		2	5	6800	0.2
19	Formwork for slab (1st part)	1	10	6000	0.2
		2	8	6800	0.2
		3	5	8000	0.2
20	Reinforcement for slab (1st part)	1	3	26 000	0.2
		2	2	26 500	0.2
		3	1	27 000	0.2
21	Reinforcement for slab (2nd part)	1	3	24 000	0.2
		2	2	24 800	0.2
22	RC for slab (2nd part)	1	1	18 000	0.8
23	RC for slab (1st part)	1	1	20 000	0.8
24	Backfilling	1	8	16 000	0.7
		2	5	20 000	1.0

The example of 24 activities is analyzed to illustrate the model capabilities in generating and evaluating optimal solution for time, cost and environmental index for construction projects. In this example, each activity can be constructed using alternative crew formations. The precedence relationships between successive activities are finish to start with zero lag time. The indirect cost a1 is estimated at $20,000 per day with an initial cost a1 of $8000.

Table 2. Optimal solutions for the example.

Project time	Total cost	EI	Crew formation option for project activities																							
			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
70	2085000	11.1	1	1	1	1	1	2	1	1	2	1	1	2	2	3	4	1	2	1	3	3	2	1	1	1
67	2089400	11.1	1	1	1	1	1	2	1	3	2	1	1	3	2	3	4	1	2	2	3	3	2	1	1	1
62	1948600	11.4	3	2	3	1	1	2	1	1	2	1	1	2	2	3	4	1	2	1	3	3	2	1	1	1

Table 3. Start and finish time for the activities with the lowest duration.

Activity	Direct cost	EI	Duration	start time	finish time

1	58000	1	14	0	14
2	34000	0.8	12	0	12
3	31000	0.9	4	14	18
4	19000	0.7	5	12	17
5	15000	0.2	14	18	32
6	20800	0.2	1	32	33
7	16400	0.2	1	32	33
8	39400	0.2	1	33	34
9	36000	0.2	1	33	34
10	24000	0.8	1	34	35
11	28000	0.8	1	34	35
12	10000	0.2	2	35	37
13	8000	0.2	5	35	40
14	75000	0.2	2	40	42
15	78000	0.2	2	37	39
16	55000	0.8	3	39	42
17	45000	0.8	2	42	44
18	6800	0.2	8	44	52
19	8000	0.2	5	42	47
20	27000	0.2	1	47	48
21	24800	0.2	2	47	49
22	18000	0.8	1	48	49
23	20000	0.8	1	49	50
24	20000	1	5	49	54

The analysis of the example illustrate the capability of the present model in generating a set of optimal resource utilization and scheduling plans that establish optimal trade-offs between project time, project cost and environmental impact helping contractors/decision makers in construction projects to select an optimal plan that satisfies the specific requirements of the project being considered. The Duration-Cost-Environmental impact trade-off Curve also illustrated in the Fig. 1.

Table 4. Start and finish time for activities with lowest environmental impact.

Activity	Direct cost	EI	Duration	start time	finish time
1	40000	0.8	20	0	20
2	30000	0.8	15	0	20
3	25400	0.7	7	20	27
4	19000	0.7	5	20	25
5	15000	0.2	14	27	41
6	20800	0.2	1	41	42
7	16000	0.2	2	41	42
8	38000	0.2	3	42	45
9	36000	0.2	1	42	44
10	24000	0.8	1	44	45
11	28000	0.8	1	45	46
12	9000	0.2	2	46	49

13	8000	0.2	5	45	50
14	75000	0.2	2	50	52
15	78000	0.2	2	49	51
16	50000	0.8	4	51	55
17	45000	0.8	2	52	54
18	6000	0.2	8	54	62
19	8000	0.2	5	55	60
20	27000	0.2	1	60	61
21	24800	0.2	2	60	62
22	18000	0.8	1	61	62
23	20000	0.8	1	62	63
24	16000	0.7	8	62	70

Table 5. Start and finish time for the activities with lowest direct cost.

Activity	Direct cost	EI	Duration	start time	finish time
1	40000	0.8	20	0	20
2	30000	0.8	15	0	20
3	25400	0.7	7	20	27
4	19000	0.7	5	20	25
5	15000	0.2	14	27	41
6	20800	0.2	1	41	42
7	16000	0.2	2	41	42
8	38000	0.2	3	42	45
9	36000	0.2	1	42	44
10	24000	0.8	1	44	45
11	28000	0.8	1	45	46
12	9000	0.2	2	46	49
13	8000	0.2	5	45	50
14	75000	0.2	2	50	52
15	78000	0.2	2	49	51
16	50000	0.8	4	51	55
17	45000	0.8	2	52	54
18	6000	0.2	8	54	62
19	8000	0.2	5	55	60
20	27000	0.2	1	60	61
21	24800	0.2	2	60	62
22	18000	0.8	1	61	62
23	20000	0.8	1	62	63
24	16000	0.7	8	62	70

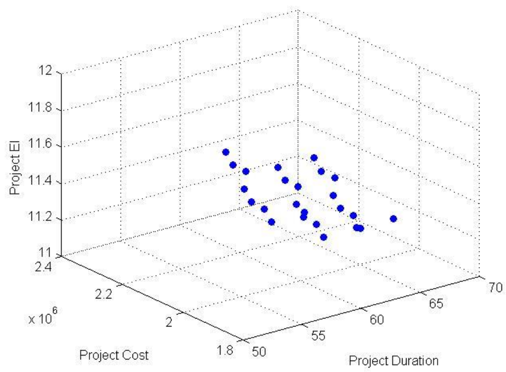

Fig. 1. Duration-Cost-Environmental Impact Trade-off Curve.

7. CONCLUSIONS

A multi objective optimization model was developed that manages the construction pollution hazards. This model utilizes evolutionary genetic algorithm to consider three objective functions project duration, project total cost and environmental index. The model helps construction professionals to generate and evaluate optimal scheduling plans that establish tradeoffs between project time, project total cost and environmental index. It can be utilized by construction authorities and environmental bodies to ensure that the total pollution of construction projects is within the permissible threshold.

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A Novel Model for Contractor Selection Decision

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Abstract

The prevailing practice on the owner's decision of contractor selection method for a procurement project has been determined by the top manager of the procurement agency via her/his comprehensive consideration of all affecting factors. Although previous researchers have proposed some analytic models to assist the decision of contractor selection method, the procurement personnel usually tend to adopt Lowest Tender (LT) for contractor selection to avoid violation of the regulation for 'Abuse of Public Power for Private Profit' without a no clear evidence to support the adoption heterogeneous procurement method (HPM), e.g., Best Value (BV) or Heterogeneous Lowest Tender (HLT). Moreover, all previous contractor selection analytic models employ the post-tendering data, it is impossible to be applied for pre-tendering decision making. To improve this drawback, the current paper proposes a Pre-tendering Graphic Analytic Model (Pre-GAM) that builds the required graphical analytic model for decision of contractor selection method using a special standardization method for historical bidding data. A real-world building construction project is adopted to demonstrate practical application and to show that the proposed Pre-GAM is able to improve the problem of post-tendering analysis and determine the correct contractor selection method.

Keywords: Heterogeneous procurement, Graphical analysis model, Standardization, Bidding data.

1. Introduction

Construction projects are usually delivered by the contractor on a contracting basis. The bidders compete for the project and the winner is awarded with the contract via a procurement process. It is therefore very important to select the most appropriate contractor for a construction project in order to achieve both successful and quality project delivery and also cost-effectiveness. Due to the regulation of Government Procurement Agreement (GPA) under World Trade Organization (WTO) [1], the public construction agencies of the Government of GPA signatory countries are required to conduct project procurement process following the international standards. In compliance with the GPA requirements, the Taiwan Government enacted the Government Procurement Law (GPL) to regularize the procurement process. There are two most commonly adopted project procurement methods defined in GPL [2]: (1) the Lowest Tender (LT)—the contractor with lowest bid wins the contract and it is more appropriate for homogeneous procurement projects; (2) the Best Value (BV)—the contractor with highest value (conceived by the procurement agency) wins the contract and it is more appropriate for heterogeneous procurement projects. Another new method for project procurement was proposed in the past decade, namely the Heterogeneous Lowest Tender (HLT), which was

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designed for procurement projects whose heterogeneity is intermediate, between heterogeneous and homogeneous [3]. According to the statistics of the Public Construction Commission (PCC) of Taiwan Government and results of previous researchers, it shows that BV and HLT outperformed the LT in project delivery performance [4], while the HLT outperforms BV in cost-effectiveness if it is adopted in the appropriate project type [5]. However, a difficult decision must be made by the procurement agency that whether the project is heterogeneous enough for either BV or HLT, since the public procurement personnel usually tend to adopt LT for procurement in order not to violate the law [6]. Under such circumstance, the public project owners will not be able to benefit from heterogeneous procurement methods. There have been several models proposed by the previous researchers to evaluate the heterogeneity of the procurement project, including P/PAM [6], P/PAM-GAM [7] and GAM-PEP [8]. One key information required for all the previous models is the Market Price Elasticity of Performance (annotated as E_m), or Market PEP [9]. The value of E_m needs to be determined by plotting the Performance/Price diagram (Q-P Diagram) with the tendering information (i.e., 'evaluated performance score' vs. 'bidding price') of the potential bidders in the heterogeneous procurement market [6]. However, the previous models required the tendering information after the potential bidders submitted their bids. This is impractical for the application of real-world projects, since the project procurement method needs to be determined before the Request for Proposal (RFP) or Request for Quotation (RFQ) is announced. Such models can be categorized as 'post-tendering evaluation models' that can be used to evaluate whether the decision on procurement method selection is appropriate or not, they are however not useful for the procurement personnel of the agency to make appropriate decision on which procurement method should be selected. In order to support the procurement method selection decision, this paper proposes a 'pre-tendering graphic analysis model', namely Pre-GAM, for determination of the most appropriate project procurement method for a construction project.

The rest of the paper is presented as follows: the important relevant works are reviewed in Section 2; then the research methodology is explained in Section 3; in Section 4, the proposed Pre-GAM is described in detailed; a real-world example of residential building construction project is selected for case study in Section 5; finally, conclusions and recommendations are addressed in Section 6.

2. Relevant Works

As addressed previously, the critical point to select the most appropriate procurement method is to determine the 'heterogeneity' of the project. The 'heterogeneity' of a project is actually determined by the capability of the contractors available in the market, who are able to deliver the project results with different performances, e.g., time, cost, image, aesthetics/appearance, operation and maintenance, managerial safety and environmental aspects, and many other factors [10,11,12]. If the procurement market is relatively highly heterogeneous, the heterogeneous procurement method such as BV and HLT should be adopted; otherwise, the homogeneous procurement method (e.g., LT) should be adopted. There have been primarily two approaches to evaluate the heterogeneity of the contractors in delivering heterogeneous project performances: (1) the subjective approach—the overall project heterogeneity is determined solely by the manager of the procurement agency, and the heterogeneous performance of the individual tender is evaluated by the Procurement Evaluation Committee (PEC) [13,14]; (2) the objective approach—the overall project heterogeneity is determined solely by the market or historical performance data of the contractors [15,6,9]. Although the subjective approach is more easily implemented, it is less reliable and doesn't guarantee the optimal result. The objective approach is more reliable and may lead to optimal decision if sufficient historical tendering data are available.

Yu and Wang [9] proposed a quantitative indicator, namely 'Price Elasticity of Performance (PEP)' or 'E', to measure the heterogeneity of the procurement market. The PEP of an individual tender was defined by Yu and Wang [12] as follows:

$$PEP = \frac{\Delta Q / Q}{\Delta P / P} = \frac{\Delta Q}{\Delta P} \times \frac{P}{Q} = \frac{1}{m} \times \frac{P}{Q} \quad (1)$$

Where, E is the measurement of PEP, Q is the measure of work performance, $\Delta Q / Q$ *is the percentage of change in work performance, P is the price,* $\Delta P / P$ *is the percentage of change in the price, and m is the slope of the tangent at point (Q, P) in the Performance/Price diagram (Q-P Diagram).*

Considering all contractors bidding for the same project as a 'market', the collective characteristics of these contractors in the market, i.e., 'market PEP' or E_m, and has been defined in by Wang and Yu [6].

Several project heterogeneity evaluation methods were proposed by Yu et al. [16], Wang and Yu [7] and Wang et al. [8] based on the indicator of market price elasticity of performance (E_m) [9]. Although the E_m provides a handy method for measuring the heterogeneity of the procurement market, it needs the tendering information to plot the required Q-P Diagram. While the tendering information is available only after the tenders are submitted by the bidders, it is not useful for the decision making when the project procurement method needs to be determined. Such a limitation is common for all PEP-based evaluation methods, e.g., P/PAM [6], P/PAM-GAM [7] and GAM-PEP [8].

3. Research Methodology

The research aims at resolving the post-tendering problem of the previously proposed PEP-based project heterogeneity evaluation methods and proposing a pre-tendering method for measuring the market price elasticity of performance (E_m) to evaluate the heterogeneity of a specific procurement project in order to select the most appropriate project procurement method (i.e., LT, BV or HLT).

In order to attain the defined research objectives, the Q-P Diagram of a procurement market has to be established with the historical tendering data, including the 'performance score (PS) vs. bidding price (BP)' datasets, which should be collected from former procurement projects of a specific owner. After data collection, the following data analysis process is conducted:

- Standardization of historical tendering data—since the historical tendering data are collected from different project, the first step is to standardize these data so that they can be utilized in constructing the same Q-P Diagram. There are two types of tendering information, the 'performance score (PS) / bidding price (PB)' of a specific bidder in the historical project. They are processed separately.
- Construction of Q-P Diagram—the Q-P Diagram of P/PAM for measuring the heterogeneity of a procurement market is constructed with the standardized historical tendering data.
- Development of procurement method selection criteria—the criteria for selecting the most appropriate project procurement method are developed according to the heterogeneity of procurement market, the project requirement of performance (PRP), and the characteristics of bidding contractors.
- Compilation of the Pre-tendering Graphic Analysis Model (Pre-GAM model) for procurement method selection—finally, the Q-P Diagram constructed based on historical tendering data, the procurement method selection criteria, and the determination of project procurement method are compiled to verify the feasibility of the proposed Pre-GAM model for the demonstrated case project.

4. Proposed Pre-GAM model for Residential Building Projects

In this section, the proposed Pre-GAM model is developed specifically to support the procurement method decision for a specific procurement agency.

4.1. Collection and standardization of historical tendering data

In the first step, the tendering data need to be collected from historical projects. The basic information of the five historical building projects are shown in Table 1.

Table 1. Basic information of the five historical building procurement projects.

Project ID	A	B	C	D	E
Building type	5-floor elev. apartment	5-floor elev. apartment	5-floor apartment	5-floor elev. apartment	5-floor townhouse
Site area (m^2)	364	496	584	167	330
Floor area (m^2)	1655	1690	1963	727	958
Budget (USD)	733,333	3100	3700	1350	2100
PRP (score %)	70	70	70	70	70

The tendering data associated with the five historical building projects are also collected and shown in Table 2.

Table 2. Tendering data of the five historical building procurement projects.

Project ID	A		B		C		D		E	
Contractor	PS	BP	PS	BP	PS	BP	PS	BP	PS	BP
I	71.27	537,000	71.98	765,667	72.27	925,333	72.48	341,333	-	-
II	-	-	-	-	70.01	915,000	70	343,000	70	522,000
III	75.38	630,667	74.89	892,333	75.99	1,073,000	75.92	388,667	75.82	603,000
IV	-	-	74.75	801,000	-	-	-	-	75.24	539,000
V	81.75	668,000	-	-	82.14	1,116,333	82.12	410,000	-	-
VI	84.72	685,000	83.83	984,000	85.32	1,160,667	-	-	84.55	668,000
VII	-	-	80.98	885,333	-	-	82.06	390,667	81.75	606,333
VIII	75.52	552,333	-	-	76.66	930,333	76.03	343,333	75.78	536,000
IX	85.02	634,667	-	-	83.92	1,082,667	84.27	393,667	-	-

Since the scopes of the five historical projects of Table 2 are different, the tendering data need to be pre-processed before they are used to construct the Q-P Diagram for the building construction procurement market of the project owner. A standardization method for PS/BP data is proposed comprising the following steps:

- Collecting tendering data from historical projects—collect the PS/BP data (e.g., the tendering data of Table 2) for the same procurement agency (or project owner);
- Categorizing the project types—group the tendering data according to project types to categorize different procurement markets;
- Standardizing the performance score (PS) and bidding price (BP) data using the Eq. (4) and Eq. (5), respectively.

Eq. (4) is used for PS standardization:

$$\mathrm{Q}_{ij} = \frac{Score_{ij}}{MaxScore_j} \times 100\% \tag{4}$$

Where, $Score_{ij}$ is the original performance score (PS) of the i^{th} contractor/bidder for the j^{th} project; $MaxScore_j$ is the maximum score (usually use 100% as the maximum score) for the j^{th} project; Q_{ij} is the standardized PS of the i^{th} contractor/bidder for the j^{th} project.

Similarly, Eq. (5) is used for BP standardization:

$$P_{ij} = \frac{Price_{ij}}{Budget_j} \times 100\% \quad (5)$$

Where, $Price_{ij}$ is the original bidding price (BP) of the i^{th} contractor/bidder for the j^{th} project; $Budget_j$ is the budget for the j^{th} project defined by the owner; P_{ij} is the standardized BP of the i^{th} contractor/bidder for the j^{th} project.

4.2. Construction of standardized Q-P Diagram

After standardizing the historical tendering data, the standardized PS(Q_{ij}) and BP(P_{ij}) for a specific contractor/bidder is obtained by averaging the standardized PS/BP data of all historical projects for this contractor/bidder. The standardized PS/BP data points of all contractors/bidders in the market are plotted as the 'x' points in the standardized historical Q-P Diagram, shown in Fig. 1.

There are some important features of the constructed standardized historical Q-P Diagram in Fig. 1: (1) the upper-bound and lower-bound both for the PS (Q) and BP(P) are outlined to highlight the boundary of the feasible tendering zone, since the performance score are required to be higher than the lower-bound and bidding price is required to be lower than the budget; (2) using the method proposed by Yu and Wang [9], the highest-quality curve (HQ) and the lowest-quality curve (LQ) are generated with general quadratic equations as depicted in the figure; (3) the market PEP (E_m) can be estimated with the slope of the straight line connecting the two intersection points of HQ and LQ. As the estimated E_m = 0.8313, thus it is a relatively homogeneous procurement market.

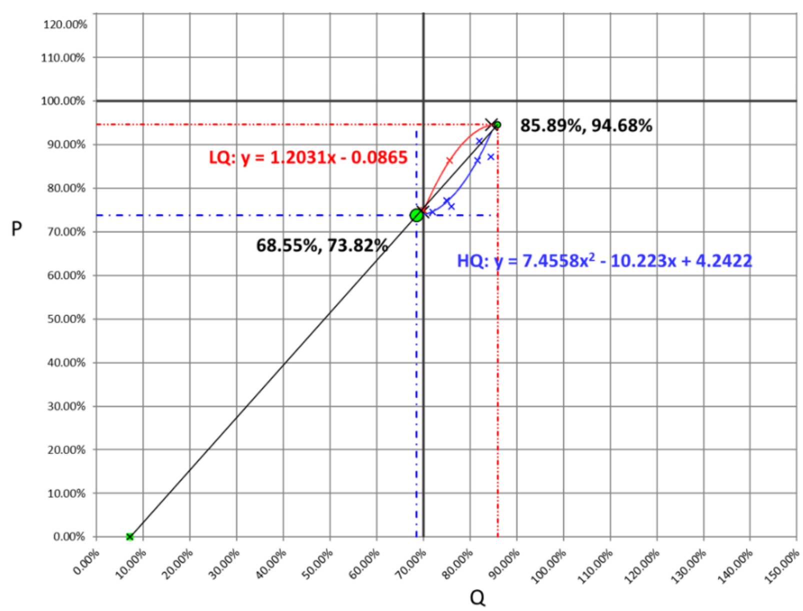

Fig. 1. Standardized Q-P Diagram of historical building projects.

4.3. Development of procurement method selection criteria

Refer to Fig. 1, where there are three critical parameters that will affect the result of procurement: (1) Lower-bound of performance (Q_{min})—only the tender with the evaluated performance Q_{min} (e.g., 70%) can be awarded; (2) Minimum of the submitted bidding prices (P_{min})—only the tender with bidding price (at least the P_{min} of the submitted bidding prices) less than budget can be awarded; (3) Market PEP (E_m)—as the higher the value of E_m, the higher the heterogeneity the market is and thus the heterogeneous procurement method should be adopted. As a result, the procurement method selection criteria are summarized in Table 3. Referring to the values of the above-mentioned parameters, the procurement method selection criteria can be planned as follows:

- If the Q_{min} is ≧ Lower-bound and E_m is < 1.0, it can be classified as a relatively lowly heterogeneous market. However, Q_{min} is < Lower-bound, it is recommended to adopt HLT to prevent the disqualified contractors from awarding, no matter the submitted prices of the bidders.
- If the Q_{min} is ≧ Lower-bound and E_m is ≧1.0, it can be classified as a relatively highly heterogeneous market. However, Q_{min} is < Lower-bound, it is recommended to adopt BV if there exists a bidder with P_{min} < 100%. However, if the P_{min} of all bidders are ≧100%, it implies that the procurement may be over-budget, thus HLT should be adopted to lower the cost.
- If the Q_{min} is ≧ Lower-bound and E_m is < 1.0, it can be classified as a highly homogeneous market and all contractors are qualified. In such a case, it is recommended to adopt LT in order to lower the cost.
- If the Q_{min} is ≧ Lower-bound and E_m is ≧ 1.0, it can be classified as a highly heterogeneous market and all contractors are qualified. In such a case, BV should be adopted if the P_{min} < 100%. However, if the P_{min} ≧ 100% it is recommended to adopt LT to lower the cost.

Table 3. Procurement method selection criteria.

Q_{min}	< Lower-bound (70%)		≧ Lower-bound (70%)	
E_m	E_m < 1.0	E_m ≧ 1.0	E_m < 1.0	E_m ≧ 1.0
P_{min} < 100%	HLT	BV	LT	BV
P_{min} ≧ 100%	HLT	HLT	LT	LT

5. Application Demonstration

In this section, a new building construction procurement project is tested with the proposed Pre-GAM for the procurement method selection of a specific building project owner to demonstrate its applicability. The testing case project is a 5-floor apartment with elevator. Project site area is 167m^2 and the floor area is 730m^2, with project budget of USD$ 483,330.

At first, the required parameters are calculated according to the historical tendering data of Table 2 and the procurement criteria of the case building construction project to determine the boundaries of the Q-P Diagram. The resulted Q-P Diagram is shown in Fig. 2

From Fig. 2, it can be noted that the required parameters from the historical tendering data are: Q_{min} = 53.19%, Q_{max} = 87.52%, P_{min} = 65.89%, P_{max} = 94.22%; and the equations for the two groups of bidders are HQ: $y=2.2957x^2-2.4422x+1.3084$ and LQ: $y=-6.1709x^2+10.8012x-3.7843$, respectively. Thus, the estimated E_m = 1.2118 > 1.0 and it is a moderately heterogeneous procurement market. The feasible procurement zone is shown as the squired in the central area of Fig. 2. There are two parts of the squire area: the green zone in the right-hand side is feasible for HLT and BV as the Q_{min} is ≧Lower-bound (70% in this case), while the pink zone in the left-hand side is feasible for LT as the Q_{min} is < Lower-bound.

After determining the feasible procurement zone, a procurement evaluation board (PEB) is organized consisting of five experienced domain experts (2 site engineers of construction firm, 1 architect, 1 procurement staff of a government agency, and 1 scholar specialized in procurement). Totally seven contractors (B1~B7) have submitted their bids to this project. The bidding documents include the bidding price and a proposal of construction plan with previous performance information for the performance evaluation by the PEB. The tendering data of the seven bidders are shown in Table 4, where the average historical performance scores (PS) of the seven bidders are shown in Row 9, while the standardized bidding prices (BP) are shown in Row 11. The standardized PS and BP are then plotted in Fig. 2 to obtain the distribution of tendering data for the bidders in the Q-P Diagram (see the dots of Fig. 2).

From Fig. 2, it is recognized that B2 with tendering information of (71.6%, 82.76%) will be awarded if LT method is adopted for procurement, while B7 with tendering information of (84.0%, 92.41%) will be awarded if BV method is adopted. The BV method is recommended since all contractors offer the performance > Q_{min}, $E_m \geqq 1.0$, and P_{min} = USD$400 < budget (USD$483,000). As a result, B7 should be awarded using BV method.

Table 4. Tendering data of the 7 bidders for the case building construction project.

PEC	Historical performance records of bidders						
	B_1	B_2	B_3	B_4	B_5	B_6	B_7
A	72	72	76	79	80	75	83
B	75	69	75	80	85	76	85
C	73	71	74	76	83	74	88
D	71	74	73	80	82	77	82
E	73	72	77	85	86	75	82
Sum	364	358	375	400	416	377	420
Standardized PS	72.8	71.6	75.0	80.0	83.2	75.4	84.0
BP (1000 USD)	410	400	400	429	447	427	447
Standardized BP	84.83%	82.76%	82.76%	88.83%	92.41%	88.28%	92.41%

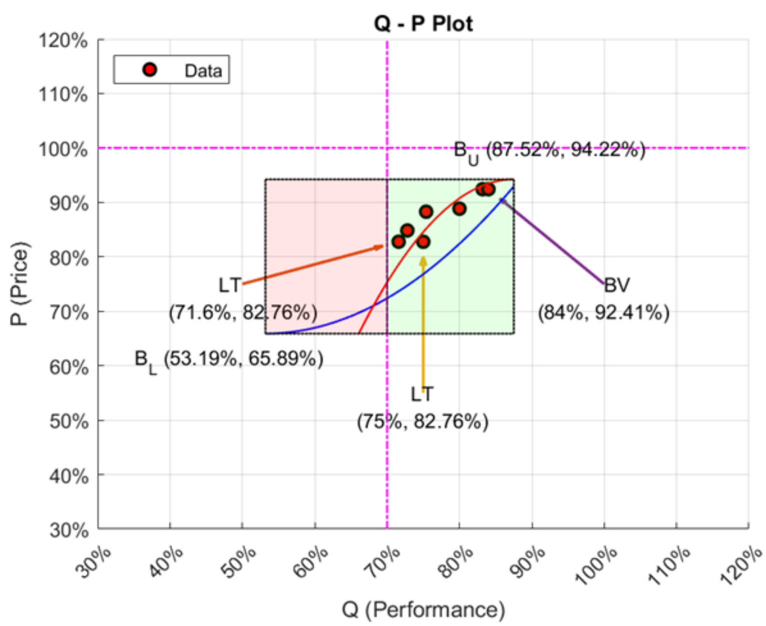

Fig. 2. Distribution of tendering data for bidders in the Q-P Diagram.

6. Conclusion and Recommendation

This paper proposes a Pre-tendering Graphic Analytic Model (Pre-GAM) to resolve the traditional difficult decision facing the procurement personnel in selecting the most appropriate one among the prevailing procurement methods, e.g., Lowest Tender (LT), Best Value (BV) and Heterogeneous Lowest Tender (HLT). The proposed Pre-GAM builds the required graphical analytic model for the decision of contractor selection method using a special standardization method for historical bidding data. It breaks the barrier of 'post-tendering decision-making' limitation encountered by the similar previous models including P/PAM [6,9], P/PAM-GAM [7], and GAM-PEP [8]. With such an improvement, the project owners will be able to enjoy the benefits of heterogeneous procurement method (e.g., BV and HLT) as the decisions of the procurement personnel are logically and systematically supported.

A real-world building construction project is adopted to demonstrate the practical application and to show that the proposed Pre-GAM is able to improve the problem of post-tendering analysis and determine the most appropriate contractor selection method. The decision of procurement method selection becomes very straightforward by plotting the tendering data of the Q-P Diagram developed by Pre-GAM. The project owner can also use Pre-GAM to evaluate their decision on procurement method selection after tendering. With such a mechanism, the procurement quality will be improved in the long run, and the benefits of the owner will be better secured.

In this paper, the Pre-GAM for a building project of a specific owner is developed. Future research is recommended to conduct similar model building procedure for different government or private owners on different types of construction procurement projects to achieve better owner benefits.

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Toward a qualitative RFIs content analysis approach to improve collaboration between design and construction phases.

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Abstract

Requests for Information (RFIs) are formal processes, used in the industry of Architecture, Engineering and Construction (AEC), to obtain information not contained or inferable in the contract documents between the design and construction phases. RFIs produce rich, precise and structured sources of information. Analysis of RFIs content can help identify recurrent problems. The goal of this article is to present a method to identify problem areas during the construction phase of AEC projects through the analysis of RFI documents. Recent advances in the qualitative analysis of document content make this quest possible and fast. This article proposes to the scientific communities and AEC industry professionals, a systematic method based on the qualitative analysis of RFIs in order to propose some types of information to consider for a design more adapted to the construction phase. An example of the application in a steel construction project demonstrates the feasibility of this method and proposes some points to consider to improve the design of steel structures.
Keywords:

Keywords: construction phase; design phase; qualitative content analysis; request for information,

1. Introduction

The success of a project in the AEC industry depends on, among other things, the quality of collaboration between designers and contractors [1,2]. Designers provide information that contractors use to create buildings that meet the customer's needs [3]. However, eighty-eight percent of decisions related to the duration and the cost of projects are made by designers [4]. They often have no experience or knowledge of the construction operations that follow and do not always provide all the information needed during the construction phase. Contractors, who are later involved in the project supply chain [5,6], will formulate RFIs to request additional information and propose modifications [7,8]. The RFIs they emit are numerous (average 796 RFIs per project [8]), and they arrive when the design phase is quite advanced. At this moment, design changes have a significant impact on the cost and duration of the project [9,10]. These impacts represent on average of 79% of the total modification costs and 9.5% of total projects costs [11]. If the information requested in the RFIs is known in advance by the designers and communicated properly in the project documents, the cost and duration of the project could be reduced. This article proposes to use qualitative content

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analysis of RFIs, to highlight recurrent information needs requested by contractors from the designers, in order to allow the designers to take this information into account when preparing construction documentation. To do this, the technique of *the qualitative analysis of the contents* is presented. Then, a methodology is proposed and a case study proposes the application of this method in the context of the steel construction industry.

2. Literature review

An RFI is by definition produced to request information or clarification from designers [12]. The quantity of RFIs depends on the quality of the design [7]. RFIs are very expensive [13]. It takes on average nine days to reply to one RFI [8]. The RFI response cost for projects of 1 - 10 million USD can range from 598 to 2 078 USD per RFI [13], which corresponds to 13 532 hours-person on average per project.

RFIs are a reliable source of information. For [12] RFIs are the standard communication approach between designers and builders. They respond to a standard writing protocol that aims to make information needs very efficient. Each RFI relates to a single technical problem. Questions and proposals for changes in RFIs are usually clear, complete and signed by an official who assumes responsibility for the request. These features of RFIs made by [12] are part of the standard steel practice code established by the American Institute of Steel Construction (AISC), and give the RFIs great credibility in terms of source of information. This quality can be exploited to improve the quality of construction projects, especially the quality of the design phase.

The use of RFIs to improve the quality of construction projects has already been the subject of some studies. [26] used RFIs to provide quantitative information on the relationship between selected RFI variables and the performance of the shop drawing production process [26]. They also determined significant associations between shop drawing production performance and production performance in terms of cost and duration. Regression techniques were used to identify individual RFI variables with significant influence on the models to predict the production performance of shop drawings.

In an analysis of the causes, effects and indicator of design flaws, [3] also proposes to quantify the causes of RFIs as a criterion for evaluating design flaws in construction projects. And in this case, it is through workshops with manufacturers that the causes of RFIs have been identified.

These studies demonstrate that RFIs can play a role in improving the quality of projects. However, there is a need for a method to analyse RFIs and retrieve the information needed to be included in design document, in order to improve the quality of the design phase.

Qualitative content analysis (QCA) is a research method that applies to textual data intended for human understanding [14]. The aim is to propose and classify knowledge and understanding of phenomena present in texts through a subjective interpretation [15]. This analysis can be done manually or automatically with software.

In manufacturing engineering, a few studies have been conducted using QCA. For example, Dong et al (2004) used analysis of the contents of design documents to study the performance of design teams [16]. Mabogunje (1997) proposed to measure the creativity of a design team based on the documents generated during the design phase [17]. Zhang et al. (2017) have developed a systematic method for delving into design journals and discovering the social relationships and performance of design teams [18]. To our knowledge, no initiatives propose to use QCA and RFIs to improve the quality of design in the AEC industry.

3. Methodology

There are three approaches in qualitative content analysis [19]: the conventional approach that describes the limited phenomena in the literature from the contents [20] ; the directed content analysis approach, used to validate or extend, a framework or theory conceptually [21] ; the summative content analysis approach used to identify and quantify certain words or themes in order to understand the contextual use of words or content [22]. This article wanted to find common themes in a series of textual documents. So, the summative content analysis approach was adopted to identify the type of information requested in RFIs.

The case study for this article is a project carried out by a steel structure design and manufacturing firm between August 2014 and December 2017. The number of RFIs for the project was 11 426. The sum of RFIs response time was 96 277 days, with an average of 8.4 working days for each RFI.

To analyze the content of RFIs, the following steps were followed (see figure 1):

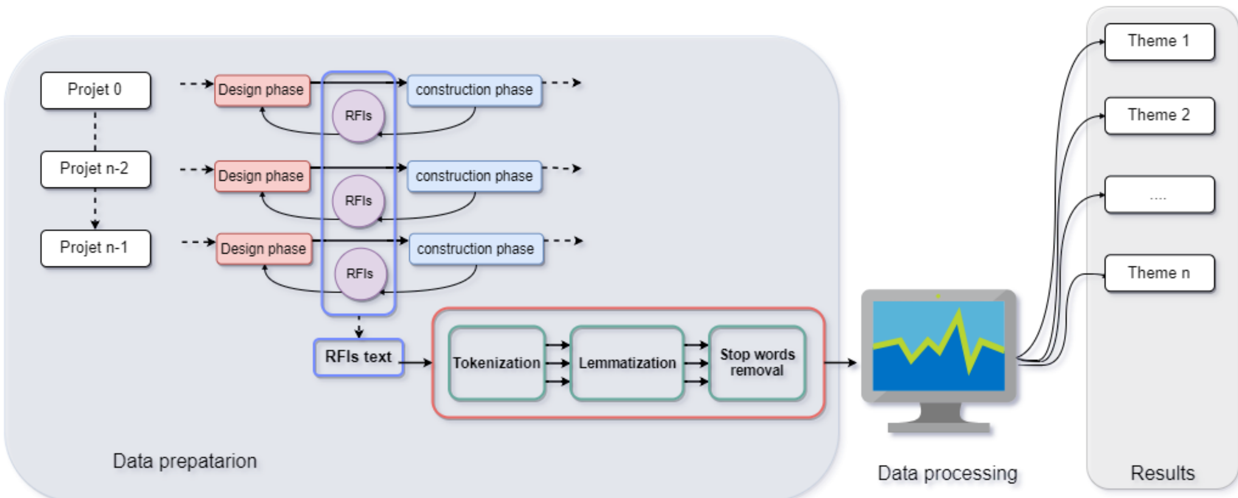

Figure 1: Methodology

3.1. Data preparation

In this step, the RFIs of previous projects are firstly collected in digital text format (docs, txt, csv). Secondly, they are treated to make them suitable for the machine [23]. This includes *tokenization, lemmatization* and *stop word removal*. The process of lemmatization or stemming, is a process of representing words in such a way as to retain only their meaning; for example, nouns are converted to singular masculine nouns, and verbs are converted to the infinitive. Stop word removal is used to simplify the text by removing words that have no major importance in communication, and, tokenization is used to divide the flow of textual content into words, terms, symbols or other significant elements called tokens [24]. After this step, the texts are ready to be processed by software.

3.2. Data processing

In this step, the most important words and themes are collected and grouped together as a table [25]. Themes represent the main problems faced by the contractors.

3.3. Data post processing.

To validate the importance of the themes found, the number of RFIs related to these themes are counted. Furthermore, the waiting time associated to each related RFI is extracted from the original database and summed for all the RFIs related to a given theme.

4. Results.

The results are as follows. The list of themes most present in RFIs and their impact on the number and response time of RFIs are presented in Table 1. Some RFIs contain several themes. For this reason, the total of the percentage is greater than 100%.

Table 1. Theme frequency for the case study

themes	Example of tokens	RFIs containing theme	% of RFIs containing theme	elapsed time for RFIs	% of the elapsed time for RFIs
total Items		11 426		96 277	
areas	area (area, areas)	5 298	46.37%	58 689	60.96%
connection	Member connection (connect, connected, connecting, connections)	3 041	26.61%	35 841	37.23%
trusses	Additional truss (trusses)	2 458	21.51%	28 499	29.60%
missing	missing (miss, missed) hole	1 556	13.62%	17 180	17.84%
detail	Complete detail (detail, detailed, detailing)	1 238	10.83%	12 002	12.47%
plate	plate (plates) size	1 165	10.20%	7 432	7.72%
weld	Dimension weld (welded, welding, welds)	1 137	9.95%	5 106	5.30%
confirm	Confirm level (confirmation, confirmed, confirmer, confirming)	900	7.88%	7 828	8.13%
Area + connection		2 137	18.70%	25 075	26.02%
Area + connection+ trusses		909	7%	12 533	13.01%

The theme “area” is the most present theme in the RFIs. It is contained in 5 298 out of 11 426 RFIs which represents 46.37% of RFIs. The theme “area” also corresponds to the highest response time of the RFIs, which means 58 689 out of 96 277 or 60.96% of the elapsed days for the RFIs. In the same order, the themes "connection" and "trusses" are the second and third themes most present in the RFIs. They are contained respectively in 26.61% and 21.51% of the RFIs and represent respectively 37.23% and 29.60% of the elapsed time for the RFIs.

Certain themes are present together in certain RFIs. The last two lines of Table 1 contains results for groups of themes. For example, 2 137 RFIs (18.70% of RFIs) contain both "area" and "connection" themes. they account for 25 075 (26.02%) of the elapsed days for responses to the RFIs. Nine hundred and nine RFIs (7% of RFIs) contain "area" "connection" and "trusses" themes and represents 12 533 (13.01%) of RFI response elapsed days. This shows that there are links between themes. Figure 2 shows how the themes are linked in pairs. The top number associated with each link represents the number of RFIs containing both themes and the bottom number the total elapsed time days for those RFIs. Thus, the missing and area theme are contained in 1 066 RFIs and represent 13 367 days elapsed.

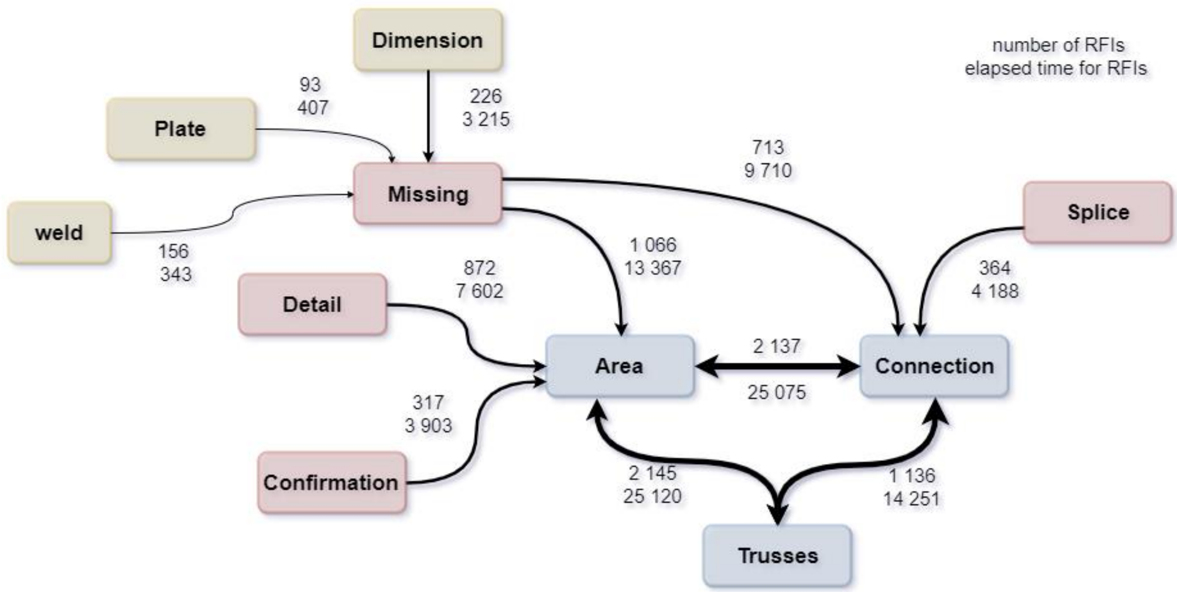

Figure 2: Link between pair of themes

5. Observations and recommendations

Observation 1: the theme “area” is present in 43% of RFIs and represents 60.96% of RFI's response time. Area does not refer to a technical problem. It would be used in RFIs to define the geographical location of structural elements. thus, the qualitative analysis of the RFIs can provide information on the geographical location which is object of most RFIs.

> Recommendation 1: if the designers identify the characteristics of the most sensitive geographical areas of the RFIs, this observation may allow them to better direct the design efforts according to the zones of similar characteristics within future projects.

Observation 2: “area” is connected to five themes (Figure 2) of which “missing”, “detail”, and “confirmation” refer to a type of information need as well as to “trusses” and “connection” themes, which refer to parts of the steel structure. The theme “area” is then the location used to request information about connections and trusses.

> Recommendation 2: the qualitative analysis of RFIs in this case study, can provide information on the types of building elements whose data are not complete at the end of the design phase.

Observation 3: on the basis of Figure 2, the set of RFIs would then express:

• The need for details or confirmation of connections,

• The need for details or confirmation regarding trusses,

• The absence of dimensions on plates or welds belonging to a connection,

> Recommendation 3-1: the qualitative analysis of the RFIs can identify, in a precise way, the information that the contractors need. This information can in the long run be the basis of the design rules. These rules can be for this example: to use for connections, symmetrical parts, standard, or even modular parts. This will significantly reduce the detail to be provided or confirmed.

> Recommendation 3-2: Recommendation 3-3: better documenting the connections of trusses could reduce the number of RFIs by almost 10% and the global response time of RFIs by almost 15%.

Conclusion:

This article proposes a systematic method that uses qualitative analysis of the RFI contents to identify the type of information to be considered during the design phase in order to better take into account the information needs of contractors. The analysis of the contents makes it possible to highlight themes present in the RFIs. in the case study in this article, the following topics were identified: “connection” “area” “trusses” “detail” “missing” “confirmation” and “splice”. In the context of steel construction, these themes represent: geographic locations that are most subject to RFIs. These themes also represent the structural elements that are the subject of the RFIs, and these themes also represent the type of information sought (missing, confirmation, detail). Consideration of these themes in the design and documentation of future projects could significantly reduce the quantity of RFIs, the cost, and duration of the project

However, this analysis does not consider synonyms and word contexts in documents. An alternative to this is to continually feed the register of synonyms and contexts, in order to improve the understanding of the contents of the documents studied.

To further this study, it would be possible to analyze several similar projects developed in the same design office to uncover contractor information need currently not provided by designers and eventually establish design rules.

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Analytic hierarchy process-based model for estimating probability of human error in design stage

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Abstract

The building information modeling (BIM) technique is used widely in construction. In general, BIM can prevent interference between different types of construction activities in advance, thereby reducing the cost of reconstruction. While it is clear that a decrease in the number of requests for information in the construction stage would have obvious benefits, there is a need to determine the effects of the investment from the planning stage. Therefore, in this study, a procedure for quantifying the design errors that occur at the design stage is proposed considering the probability of the human errors concept. To achieve this, factors for evaluating human errors can arise during the drawing stage. Based on these factors, an analytic-hierarchy-process-based human error probability estimation model is suggested. Based on the factors affecting the error in the design stage, we construct a hierarchy and calculate the relative importance based on the probability and assess the effectiveness of each risk control option. It is expected that if the model presented in this study is linked with the loss cost data for each factor, a loss estimation model at the design stage can be developed.

Keywords: analytic hierarchy process; building information modeling; return on investment; human error estimation

1. Introduction

Building information modeling (BIM) is being adopted in the field of construction on a wide scale. It has the advantages of BIM, which can be used to calculate the construction cost and the construction activities necessary based on the information inputted in advance, thus helping prevent conflicts between the construction stakeholders that can occur during the design stage. In addition, BIM makes it possible to reap economic and temporal benefits by reducing the number of requests for information (RFIs) that are generated at the construction stage; this is because it requires the collection and reviewing of all the design drawings to be exchanged between the architect, civil engineer, mechanical, electrical, and plumbing engineering personnel at the design stage.

However, despite the many advantages of BIM, it is not widely used in Korea. Although the Korean government encourages the use of BIM through policy incentives, construction companies are reluctant to preemptively invest in BIM because they are not sure of whether the initial-investment-to-profit ratio is effective or not. In other words, companies want to see proven return on investment(ROI)s before they invest in BIM.

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Most existing studies on the ROI of BIM [1-7] have focused on ROI after construction is completed. These studies show that it is advantageous to invest in BIM by calculating the financial profit and comparing it to the investment required based on analyses of cases where construction had been completed. While it is clear that there are obvious benefits to the decrease in the number of RFIs, there is a need to determine the effects of the investment from the planning stage if BIM is to be positioned as part of the overall process in the construction sector as well as a computer-aided design tool.

Therefore, in this study, a procedure for quantifying the design errors that occur at the design stage is proposed considering the probability of human errors.

2. Research method

This research is conducted as follows.

- Categorizing the evaluation factors - Categorize factors that could potentially lead to errors in the planning and design phases.
- Developing the hierarchy—A hierarchy for analytic hierarchy process (AHP)-based analysis is constructed with the goal of minimizing design errors.
- Determine the types of human errors—Determine the types of behaviors owing to which various types of errors may occur. In this study, only the skill-, rule-, and knowledge- approaches proposed by Rasmussen [8] were used.
- Determine the probability of occurrence of errors—Based on the probabilistic data presented in Step 3, determine the probability that a human error might occur while performing the task in question. Further, using this information, determine the probability of occurrence of the human error assigned.
- Determine the severity of occurrence—The severity of a human error should consider the consequences of the error on the design procedures. The severity is quantified by taking into account the delay and financial loss caused by the error.
- Determine the risk control options (RCOs)—Determine the administrative, institutional, and systematic measures that can be taken to minimize design errors.
- Final analysis—Use the proposed method to determine the optimal RCOs and their respective effects.

3. Model description

3.1. Categorizing the factors

In order to evaluate the proposed method, the behavioral errors that may have occurred at the design stage are set. The primary error categories and the related behavioral characteristics, as well as the probabilities of occurrence of these errors, were established based on the results of a previous study by Rasmussen [8]. In this study, the errors were categorized as mental, physical, knowledge-related, and environment-related errors. Detailed sub-factors are listed in Table 1.

Table 1. Descriptions of behavior factors and probabilities of occurrence of different types of errors

Category	Variance	Definition of sub-factors	Types of human error	Probability of occurrence
Mental	M1	Mistake (not intended)	Skill-based	5.00E-03

	M2	Attitude for doing work	Rule-based	5.00E-02
	M3	Personal concern	Skill-based	5.00E-03
	M4	Disagreement with team members	Knowledge-based	5.00E-01
Physical	P1	Lack of physical strength due to excessive work	Skill-based	5.00E-03
	P2	Unexpected health problem	Rule-based	5.00E-02
Knowledge	K1	Lack of relevant knowledge regarding design	Knowledge-based	5.00E-01
	K2	Lack of knowledge regarding collaboration	Rule-based	5.00E-02
	K3	Lack of ability to deal with graphics-related software	Knowledge-based	5.00E-01
	K4	Lack of ability to create design drawings	Knowledge-based	5.00E-01
	K5	Lack of skills to operate computer	Knowledge-based	5.00E-01
Environmental	E1	Low salary	Rule-based	5.00E-02
	E2	Related to working environment (human relations with team members)	Knowledge-based	5.00E-01
	E3	Excessive customer demands (frequent changes to design)	Skill-based	5.00E-03

3.2. Developing hierarchy

Based on the evaluation factors, a hierarchy of error is developed to minimize the human errors in the design phase.

3.3. Determining human error types

The definitions of the types of human errors [9] considered in this study are as follow:

Skill-based behaviors depend mostly on the operator's practice level while performing the task in question. These errors tend to be related to routine activities under familiar circumstances.

Rule-based behaviors are at work when the operator does not have adequate practice performing the required task, but has clear knowledge of what the procedures involves. Rule-based errors are related to the misapplication or inappropriate use of problem-solving rules.

Knowledge-based behaviors are related to instances where the operator needs to understand the situation, interpret information, or make a difficult decision. Also included in this category are cases where a procedure is not well defined. Knowledge-based errors are related to performance in new situations.

3.4. Determining probability of occurrence

3.4.1 Upper hierarchy

As suggested in Fig. 1, the probability of occurrence and severity make up the two elements of the matrix. These two elements are compared to determine the weighting vector for each element. Using the comparison scale given in Table 2, the importance of the two elements can be determined. In this study, it was assumed that the two elements have the same importance. The matrices can be written as follows:

Upper hierarchy = $\begin{bmatrix} 1 & 1 \\ 1 & 1 \end{bmatrix}$ and weighing vector =$\begin{bmatrix} 0.5 \\ 0.5 \end{bmatrix}$

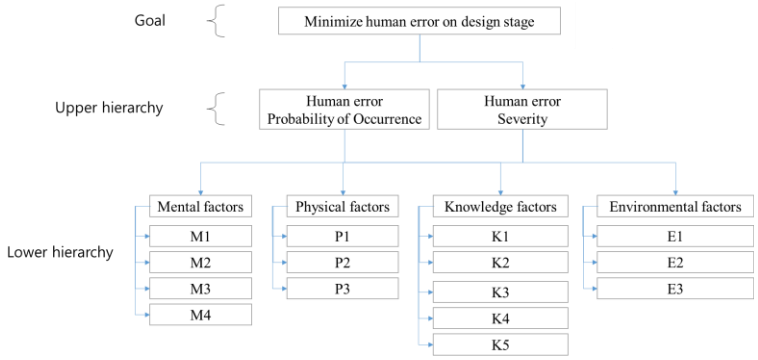

Figure 1. Hierarchy structure of the model

3.4.2. Evaluation of probability of human error

First, the importance of each factor (mental, physical, knowledge-, skill-, or environment-based) is determined. Using Table 1, the matrix shown below is obtained for the probability importance among factors.

$$\text{Probability} = \begin{bmatrix} 1.00 & 0.33 & 5.00 & 3.00 \\ 3.00 & 1.00 & 0.33 & 1.00 \\ 0.20 & 3.00 & 1.00 & 3.00 \\ 0.33 & 1.00 & 0.33 & 1.00 \end{bmatrix}$$

The weighting vector and normalized vector are determined by considering the weighting vector obtained in the matrix in section 3.4.1 and are as shown below:

$$\text{Weighting vector} = \begin{bmatrix} 0.3520 \\ 0.2561 \\ 0.2829 \\ 0.1090 \end{bmatrix} \text{ and Normalized vector} = \begin{bmatrix} 0.1760 \\ 0.1280 \\ 0.1415 \\ 0.0545 \end{bmatrix}$$

Table 2. Comparison scale

Determination value	Judgment Criteria	Determination value	Judgment Criteria
1	Both elements are of equal importance	1/3	Top weakly more important than left
3	Left weakly more important than top	1/5	Top moderately more important than left
5	Left moderately more important than top	1/7	Top strongly more important than left
7	Left strongly more important than top	1/9	Top absolutely more important than left
9	Left absolutely more important than top		

The matrices for the probability of occurrence of each sub-factor are determined as shown below:

$$\text{Mental} = \begin{bmatrix} 1.00 & 0.56 & 1.00 & 0.11 \\ 1.80 & 1.00 & 1.80 & 0.20 \\ 1.00 & 0.56 & 1.00 & 0.11 \\ 9.00 & 5.00 & 9.00 & 1.00 \end{bmatrix}, \quad \text{Weighting Vector} = \begin{bmatrix} 0.0781 \\ 0.1406 \\ 0.0781 \\ 0.7031 \end{bmatrix} \text{ and Normalized vector} = \begin{bmatrix} 0.0138 \\ 0.0248 \\ 0.0138 \\ 0.1238 \end{bmatrix}$$

The same procedure is repeated for the remaining sub-factors.

3.4.3. Evaluation of severity of human errors

The severity of the human errors related to the factors (mental, physical, knowledge-, skill-, and environment-based) is determined. The probabilities are compared based on the probability suggested in Table 1; however, the severity can be calculated through questionnaires filled by an expert group. In this study, it was selected according to the researchers' experience because it only explains the possibilities of the model. The remaining calculations are the same as those for determining the probability.

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3.5. Risk control options (RCOs)

In this study, several RCOs are proposed for reducing the design errors arising from human errors. This is done based on the AHP. These RCOs were evaluated against the lower hierarchy. For example, an arbitrary scale (1–10) was used to compare each RCO, with 1 meaning not effective and 10 meaning most effective. In order to evaluate these effects, we considered multiple factors such as cost, applicability, and efficiency. The RCOs used for evaluation were as follows:

- RCO1 – Introduction of a systematic management system for revised drawings
- RCO2 – Introduction of a cross-checking procedure for drawings
- RCO3 – Introduction of systematic work instructions (manual)
- RCO4 – Increasing the capacity through regular training
- RCO5 – Providing assistance with new computing technology

The matrices for the effectiveness of each RCO were calculated as below.

The behaviors are placed in the left column, the RCOs are placed in the top row, and the effects of the RCOs are evaluated based on the criteria listed in Table 2. For example, the effectiveness of the RCOs in the case of mental errors can be evaluated as shown in Table 3.

Table 3. Example of evaluation of effectiveness of RCOs

	RCO1	RCO2	RCO3	RCO4	RCO5
Mental1	8	9	5	8	7
Mental2	3	7	6	8	2
Mental3	1	1	2	3	5
Mental4	3	1	8	1	5

Next, we multiply the matrix of the evaluation results with the previously computed normalized matrix. The probability and severity of occurrence are listed in Table 4.

Table 4. Normalized results of effectiveness of RCOs

Factors	Probability					Severity				
	RCO1	RCO2	RCO3	RCO4	RCO5	RCO1	RCO2	RCO3	RCO4	RCO5
Mental1	0.0030	0.0033	0.0019	0.0030	0.0026	0.0030	0.0033	0.0018	0.0030	0.0026
Mental2	0.0029	0.0067	0.0057	0.0076	0.0019	0.0021	0.0049	0.0042	0.0056	0.0014
Mental3	0.0011	0.0011	0.0023	0.0034	0.0057	0.0021	0.0021	0.0042	0.0063	0.0105
Mental4	0.0206	0.0069	0.0550	0.0069	0.0344	0.0198	0.0066	0.0529	0.0066	0.0330
Physical1	0.0020	0.0080	0.0159	0.0040	0.0159	0.0014	0.0056	0.0111	0.0028	0.0111
Physical2	0.0107	0.0179	0.0286	0.0036	0.0214	0.0125	0.0209	0.0334	0.0042	0.0250
Knowledge1	0.0056	0.0067	0.0079	0.0090	0.0045	0.0082	0.0082	0.0082	0.0082	0.0082
Knowledge2	0.0011	0.0013	0.0013	0.0017	0.0013	0.0673	0.0673	0.0673	0.0673	0.0673
Knowledge3	0.0052	0.0026	0.0052	0.0130	0.0078	0.0237	0.0237	0.0237	0.0237	0.0237
Knowledge4	0.0061	0.0031	0.0046	0.0107	0.0092	0.0261	0.0261	0.0261	0.0261	0.0261
Knowledge5	0.0026	0.0026	0.0052	0.0155	0.0078	0.0162	0.0162	0.0162	0.0162	0.0162
Environmental1	0.0006	0.0006	0.0026	0.0038	0.0006	0.0003	0.0003	0.0012	0.0019	0.0003
Environmental2	0.0052	0.0052	0.0156	0.0130	0.0026	0.0044	0.0044	0.0132	0.0110	0.0022
Environmental3	0.0010	0.0013	0.0010	0.0002	0.0010	0.0035	0.0042	0.0035	0.0007	0.0035

Table 5 lists the degrees of effectiveness of the RCOs based on the summation of each calculated value for a particular factor. For example, the effect of achieving goals related to management activity through RCO1 is 13.91% while that for RCO2 is 13.27%. This can also be interpreted as meaning that the effectiveness when the "mental" factor is managed using the suggested RCOs is 35.20%.

Table 5. Results of evaluation of RCOs

Evaluation factors	RCO1	RCO2	RCO3	RCO4	RCO5	Sum
Mental	5.46%	3.50%	12.80%	4.24%	9.21%	35.20%
Physical	2.66%	5.23%	8.91%	1.45%	7.36%	25.61%
Knowledge	4.28%	3.64%	4.88%	9.38%	6.10%	28.29%
Environmental	1.51%	1.60%	3.71%	3.06%	1.03%	10.90%
Sum	13.91%	13.97%	30.29%	18.12%	23.70%	100.0%

4. Conclusions and future work

In this study, a method is proposed for calculating the effects of the final decision-making on the errors that can occur during construction activities and the methods used to manage them. This is done by introducing the concept of probability to the existing AHP method. The probabilities used are the three types of probabilities proposed by Rasmussen [8]. However, more accurate calculations are possible using the results reported by Dhillon [10] or the calculated probability values. In addition, if a clear RCO is set, the analysis of the effects will be more accurate. It is expected that if the model presented in this study is linked with the loss cost data for each factor, a loss estimation model at the design stage can be developed.

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Application Development to Reduce Generation Time for Punch List

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Abstract

With the recent improvement in the quality of life, more and more people are now demanding higher quality in terms of construction projects. Accordingly, construction techniques and construction control techniques have advanced. Recently, various construction project quality control techniques have been introduced. However, due to the non-optimized processes, it is difficult to commercialize these techniques. The biggest problem of the existing task process is 'the duplicated input'. The 'input at the site', the first phase of the 'duplicated input', is entered by typing within the application. However, due to the characteristics of the tasks on a construction site, it takes a long time and thus is inappropriate. Second, 'the input at the office' is problematic as it requires manual input for each sentence. The first problem was improved by changing the on-site typing method to 'input by item selection'. The second problem was improved by using 'automatic sorting' for the on-site input within the application. When the improved task process was implemented in the application, the working hours were reduced by about 18.4%.

Keywords: quality management, application, punch list, reduction of working time ;

1. Introduction

In South Korea, several information technologies (ITs) are being introduced to building construction projects to enhance such projects' efficiency. Various studies have been conducted to promote building construction tasks using mobile applications. One example of such approaches is to generate a punch list of construction defects during a project based on an application. This notwithstanding, there is still much room for improvement. As such, this study aimed to propose a plan to improve the efficiency of punch list generation

2. Generation of a Punch List for the Quality Management of a Building Construction Project

In South Korea, a punch list is generally generated to manage the quality of a building construction project at the construction site. A punch list is a document that lists the construction defects found through construction quality inspection following the project's completion. These construction defects are documented for repair and maintenance work. To generate a punch list, an application is usually employed at the site. Most of the currently used applications allow the entering of the construction defect contents and images (Fig. 1). The manager in charge of generating a punch

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list enters the construction defect contents to the site using a smartphone, and then completes the list at the site office on a desktop PC.

Fig. 1. examples of punch list generation

Fig. 2. improved input method

3. Punch List Generation Problems and Improvement Plan

3.1. Problems of the currently used applications for punch list generation

There are three types of applications that are currently being used at construction sites in South Korea for punch list generation. Of these, this study focused on D-App, the most widely used and most downloaded application. The analysis that was conducted in this study showed that the generation of punch lists using these existing applications encounters the following problems:

- Entering the defect contents was inconvenient as the user needed to type them into the application. The generation of a punch list on D-App requires the user to enter the defect contents by typing. Such a method requires a large number of key touches, thus lengthening the time required for completing the tasks.
- The generation of a punch list using the existing applications for such are not very efficient. The punch list is generated both at the site and in the office, which degrades the efficiency of the task completion. The survey conducted in this study showed that the users enter the construction defect contents using an application, and generate the punch list again on a desktop PC in the office, thus performing the task twice.

3.2. Improvement of punch list generation

This study aimed to improve the existing method of generating a punch list, as cited below.

- The input method was improved by changing from typing to selecting items (Fig. 2). Accordingly, the time that it takes the user to enter the contents was reduced, and the whole task of punch list generation was made more convenient.
- The punch list generated at the site can now be used as is. The information on the construction defects entered at the site is transmitted via e-mail, and in the office the user can then simply produce a punch list using the data obtained from the sent e-mail. Shown in Fig. 4 are the changes in the flowchart with the improvement of the punch list generation.

3.3. Development of an application based on the punch list generation improvements

In this study, a new application (P-App), which improved the problems of the existing punch list generation method, was developed. Shown in Fig. 3 is a part of the user interface of P-App. The basic functions of P-App are as follows. As shown in Fig. 3a, the main screen consists of three parts: “Generating a List,” “Punch List,” and “Preferences.” Fig.

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3b shows the method of entering the construction defect contents using the application. If necessary, images can be taken and added to the list. Fig. 3c shows how to enter the construction defect contents by simply selecting items. New contents can be added using the + button, as shown in Fig. 3b. With the use of the button on the upper right corner and after the accomplishment of the confirmation procedure shown in Fig. 3d, the list can be added as shown in Fig. 3e. Once the list is completed, it can be sent as a Microsoft Excel file in an e-mail, as shown in Fig. 3f.

Fig. 3. user interface of P-App

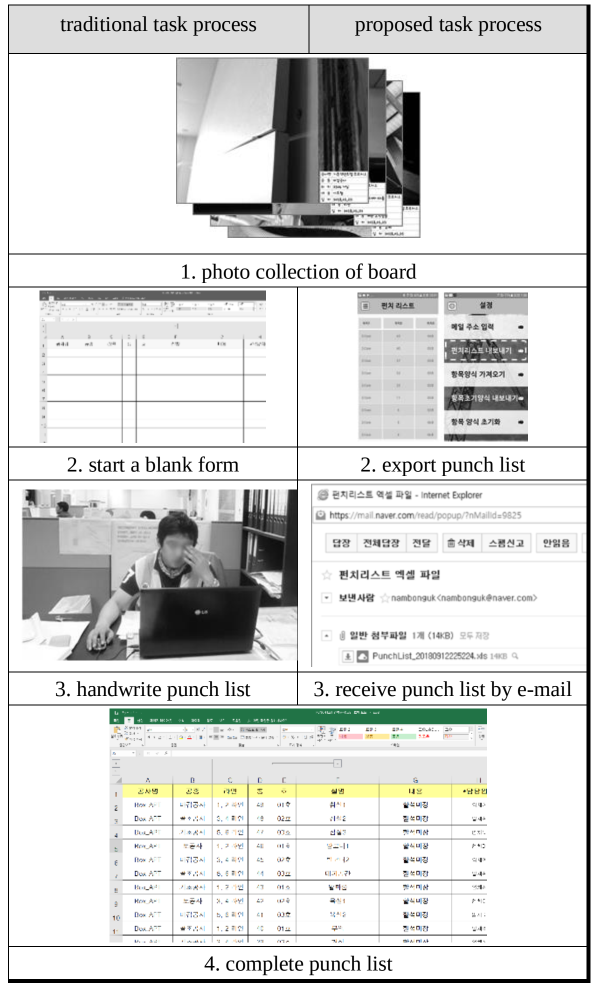

Fig. 4. proposed punch list procedure

4. Analysis of the Changes in the Punch List Generation Tasks

4.1. Improvement of the punch list generation procedure

Using the P-App developed in this study, the punch list generation procedure was improved. As shown in Fig. 4, the existing method only allowed for the entering of images taken on the site and the construction defect contents, but the subsequent task, the generation of a punch list, cannot be performed onsite using such a method. Using the application developed in this study however, the entering of the construction defects and images as well as the generation of a punch list can be performed at the same time. This will result in removing duplicated tasks and improving the overall task procedure.

4.2. Analysis of the time it takes to generate a punch list

In this study, the change in the task efficiency based on the new application was analyzed by applying the application to an actual building construction case. The case used for the analysis was an apartment construction project (A Project), the most usual construction type in South Korea. A Project developed buildings for 1,498 households in Suwon, Gyeonggi-do. For quality management, A Project generated 22,744 punch lists using the D-App.

To analyze the difference in task efficiency by application type, the time that it took to generate a punch list in A Project was determined. Shown in Table 1 are the punch list generation procedures by application type. Based on Table 1, the time that it took to generate punch lists in A Project was determined, as shown in Fig. 5. Using the P-App developed in this study, the time that it took to generate a punch list was reduced by 18.4% compared to the time that it took to do the same with the D-App

Table 1. Punch list procedure

Task information	D-App	P-App
Preparing app	1min.	20min.
Move	5min/1e.a.	5min/1e.a.
App utilization	0.9mun/1e.a.	0.3min/1e.a.
Office movement	5min.	5min.
Generation punch list	0.6min/1e.a.	1min

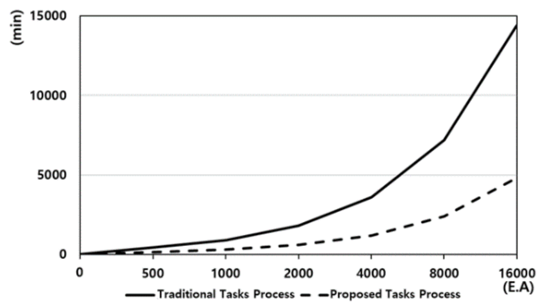

Fig. 5. analysis of punch list generation time

5. Conclusion

A wide range of information technologies (ITs) have been introduced to the management of building construction projects. Applications have also been introduced for the quality management of various tasks, including punch list generation. It has been shown, however, that app-based quality management has not been sufficiently optimized. As such, this study aimed to develop an application with which to improve the efficiency of punch list generation. Furthermore, it was determined that the developed application could reduce the time that it takes to generate a punch list. Below are the key results of this study.

- The problems of the existing applications for punch list generation were analyzed. The problems were the inconvenience in entering construction defect contents and the inefficiency of punch list generation.
- An application with which to improve the efficiency of punch list generation was developed.
- The new application was used to improve the punch list generation tasks. The input method was changed from typing to item selection, and the time that it takes to generate a punch list was reduced.
- The time that it takes to generate a punch list based on the introduction of the new application was analyzed. Compared to the existing applications, the new application reduced the time by 18.4%.

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Artificial Intelligence in Construction Management – a Perspective

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Abstract

Efficient organization of construction services seems to be a complex task, limited by the capabilities of human intelligence. During the seventies based on e.g. the development of fuzzy technologies by Zadeh, the rise of expert systems gave new hope to innovative approaches to solving complex situations in project management. As history teaches, since then no real advance could be observed regarding this concept. Nowadays construction and real estate projects have become larger, thus more complex and risky, time schedules have become tighter as have the available budgets. With this the need of support of the organizational challenge has increased significantly. In this context and supported by the presently available computing power as well as on the basis of a presumably complete model of the building including the construction process with an Building Information Model (BIM), the idea of support by Artificial Intelligence has gained importance again and new hopes as well as fears have come to life.
Prior to explicit attempts to construct tools for construction management, an investigation of the principal needs of organizational support as well as the possibilities provided by Artificial Intelligence is required in order to prepare the ground for future development.
In this paper the principle understanding of complexity based on locality developing into emergent behaviour of the organization of construction projects is presented and mirrored to the expectance towards artificial intelligence operating on a Building Information Model (BIM). This investigation makes use of the theory of systems to model the behaviour of complex systems as well as of commonly used approaches offered by artificial intelligence concepts, e.g. neuronal networks, machine learning algorithms and rule-based decisions within a complex context. On this background the feasibility of improvement in gaining efficiency in construction management organization is elaborated and reviewed.

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Keywords: Building Information Model (BIM); complexity; construction management; real estate management; Artificial Intelligence;

1. Introduction

The term Artificial Intelligence (AI) is used since the 50ties of the last century. Again and again the upcoming equality of natural and artificial intelligence has been predicted and postponed. Concepts of AI have been developed according to the understanding of natural intelligence, and received great acknowledgement but again and again human mind has been understood a little bit further and therewith artificial attempts failed to keep up. With the upcoming rise of available computing-power ancient principles have been revitalized and are now reaching heights which truly seem to be able to compete with the human brain. Not much of the fundamental concepts has changed, but the complexity of the outcome reveals astonishing heights.

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During the upcoming of computer sciences, the idea of the complex task of managing unique projects with the support of computers was established. Soon, algorithms on the basis of Theory of Graphs allowed computing CPM, MPM and PERT networks. Still resting on strict definitions of situations, solutions were not achievable in many cases due to the often contradictory character of bivalent restrictions or to causal loops inhibiting determined procedures. As a consequence, fuzzy variables were introduced first on PERT diagrams [14, 23], where durations were determined by BETA-distributions, not on the solid ground of measured probabilities, but on estimations given by experienced managers. Later, Zadeh [26] introduced the concept of fuzzy-sets in order to model vaguely determined parameters as well as equivalently vague interactions, provided by a vast range of expert-knowledge. The main problem occurred to be not the well-working maths but on the one hand the procedure of obtaining sufficiently general and numerous situations to derive fundamental knowledge from and on the other hand the applicability of equivalently vague resulting instructions and targets for the final execution.

2. Construction Management as Complex Task

Artificial Intelligence seems to be a promising approach to solve problems, which overchallenge a human mind, be it due to the sheer volume of data, of processes or, in particular, the given complexity. Issues concerning the volume of a task are understood as predestined for computer applications while the term of complexity is different. Definitions of complexity are given e.g. in [8, 13, 19, 24]. They are mainly referring to behaviour of a system, which can not be described by the local properties or next neighbour interactions but by the total interacting system. Such behaviour is in contrast to locality understood as being emergent. In former times, as long as the volumes of construction projects have been limited, and due to a fairly strict separation of contractual work into trades, this task was manageable, however with some effort and not always successfully. Meanwhile, Construction and Real Estate projects are becoming much more voluminous, as are budgetary and temporal margins becoming tighter, e.g. with large turnkey-ready buildings. With this development and clearly indicated by the observation of an increasing number of publicly known disastrous projects, Construction Management on this scale is possibly in fact beyond the scope of a limited human mind [11]. Construction Management is just the efficient organization of a large number of participating people or groups as well as an equally large number of technical construction elements or, more abstractly, virtual units like activities, services and cost, including their vast set of nonlinear relationships [22]. Clearly, the behaviour of a system "Construction Project" is emergent [4] and the task of Construction Management would be to lead it nonetheless with high certainty within a very narrow corridor to a very tight goal in terms of time and cost [5]. If this is beyond capabilities of man, will it be within the scope of Artificial Intelligence?

3. Technical Approaches to Model Artificial Intelligence

Since nevertheless "artificial" implies the creation of this "intelligence" by the human mind, first, the principle methods and algorithms need to be laid out:

3.1. The Principle of Industriousness: Procedural Formulation

With procedural respectively imperative formulation of tasks [27], a set of rules is elaborated in a way that a complex task is treated correctly and the correct results are provided. These rules and instructions, developing from a well-defined state to a next also well-defined state, are processed for huge volumes of data or a long time, possibly repeatedly or iterative. The resulting behaviour looks like "AI", but all the "I" is pre-programmed including all foreseeable particular and specific situations. This is applied with classical software programming processes and, thus, poses the problem of formulating in short, but absolutely strict, the rules and instructions which represent the complete and complex behaviour. In Construction Management this concept is made use of, e.g. within a costing software, where values of single items are precisely assigned to a node within an unambiguous structure and locally treated there according to very clear rules. Only the application of the repeated instructions of where to receive the values from, how to process and in particular where to cumulate allows for an overall correct result of costing [22].

Comment and evaluation for Construction Management: This approach is widely used in Construction Management but still based purely on human intelligence: Any not precisely understood development of a system cannot be brought down to instructions and therefore never be actively modelled. Therefore, this offers no progress on tackling complexity beyond human capabilities.

3.2. Virtual Intelligent Behaviour: Object-Oriented Formulation

In contrast to imperative formulations where the creative mind is located outside the system, object oriented design facilitates intrinsic behaviour [27]. A large number of local rules connecting objects to determine properties of a destination object are set up as being valid and correct. Due to their strictly local character their validity can easily be proven. Applying these to a large set of data, i.e. objects with their properties, recursively or iteratively, represents the behaviour of the system [2]. The interaction of the local rules and the un-predetermined type and structure of the data-set leads to emergent behaviour. This again is true as long as the set of rules is locally true and complete. The emergent behaviour reflects the correct situation and looks intelligent. However, a system like this produces "intelligent" behaviour, as long as simply emergent behaviour is intelligent and not just complex. It is in fact just unintelligible. If the local rules are well-determined, i.e. the system perfectly well-known, then the resulting character is in fact reflecting the reality to be expected (besides some artefacts due to the imperfect modelling and execution of the local rules). This is the fundamental approach to simulation, mainly used with iterative processing.

Remark: If otherwise the behaviour to be modelled is known and the local rules to achieve this are to be developed, things become more difficult. This would be the case with object-oriented programming, which is only applicable if the behaviour is clearly assignable to a limited number of local rules [2].

The challenge of intelligence modelled on the basis of interacting objects is that in particular correctness and completeness of the set-up are fairly difficult to ensure but nonetheless inevitable. In Construction Engineering this concept is used e.g. for all sorts of Finite Element methods, in Construction Management as the basis of the Ford-Algorithm for positioning activities on the time-axis, simulation of processes [27], or for clash detection within a Building Information Model (BIM) [3].

Remark: This approach poses a specific problem: Trying to create such systems leads to making the users as well as the constructors slaves to it, even if the complex behaviour is found not to match the observed or required reality. This is mainly because there are no ways to track an error back to a single rule to be modified. Observing the emergent behaviour, in particular the not matching part of it, allows only to test-wise introduce additional rules and observe the hopefully improved result again. The connection between result and input is a very strict one-way road.

Comment from the view of Construction Management: This approach is also widely used in Construction Management. In particular, where all the local information is given, clearly complexity is only the emergent behaviour of the total system controlled by nothing else [28]. However, completeness of the primary description of the system is essential to this understanding since complexity implies the characteristic of irreducibility, i.e. missing a single element or interaction may change the whole picture to an incalculable degree.

3.3. Neuronal Networks

A completely different approach is maintained by the concept of neuronal networks. This is an attempt to fight a way back from observed emergent behaviour to local rules. Intelligent behaviour can be observed in the real world, e.g. based on intelligent decisions of clever individuals. Methods like neuronal networks construct weighted sets of rules, capable to reproduce these decisions and extrapolate this behaviour to proximate situations. This is an attempt mimicking the learning process of a human brain. However, a fundamental model needs to be constructed, utilizing a set of parameters which are to be optimized for a proper representation of correct implications. This procedure implies that the pre-constructed model is correct or at least sufficiently general to cover the given issues. With neuronal networks the underlying model is a multi-layered linear combination of possibly nonlinear triggering elements. Such a pre-set is already restricting the possible output, nevertheless promising. The Neuronal Network approach is particularly successful with optical and acoustical pattern recognition tasks. However, the developing processes require a huge set of information to learn from, in particular somewhat orthogonal rules in order to cover a given space of situations. Due to the requirement of comparability of solution spaces, the resulting intelligence is limited to answers already experienced by the learning material, never reaching beyond these.

Comment from the view of Construction Management: This approach is fairly close to the historical attempts tackling Construction Management during the 1980s [18]. That time it suffered from both the lack of sufficient data to learn from as well as the computing capacities to process this volume accordingly. Both seems to have increased largely by now. So, speaking of AI to cover Construction Management issues focusses solely on the neuronal network approach.

4. Fundamental Approach to AI

Artificial Intelligence is expected to decide better as or equal to a human being exposed to the same situation and parameters, i.e. based on an identical level of existing information. On the background of the second law of thermodynamics within a closed system the total entropy S will only increase. Understood as a measure of information according to Shannon [21] we have $S = \ln_2(I)$ and therewith the main law of Informatics stating that information can only be lost, i.e. destroyed, never generated. In particular, this allows AI principally not to generate knowledge, which is not primarily existing, but only to process existing information into decisions based on mechanistic rules.

Remark: The technical approaches to AI discussed previously take account of this principle.

In contrast to this, an intelligent (human) mind might be able to contradict this principle. Szilard [25] approached a comparable situation investigating the existence and entropic situation of the Maxwell Demon. Taking into account the requirement of entropy to accomplish the measurements a decision is based on, the gained entropy exactly balances the spent entropy and thus proves the validity of the Second Law of Thermodynamics even for the action of an intelligent mind. However, this applies only for deterministic reasoning where rules and information are given and all the decisions are purely based on these. So far, this again comes down to pure industriousness. Bringing in the creative mind, where we assume decisions to be made on the background of taste and fantasy, such consideration might not apply. In particular, Ebeling et al [7] investigated generating information of different types by e.g. an intelligent mind, a creative being and finally self-organizing mechanisms. Considering intelligent and creative beings, this may happen on the entropy cost of the existence of themselves, but self-organisation presents itself as revealing information which was just hidden within the system and had no opportunity to establish visibly. Artificial Intelligence therefore is understood to operate within a closed system where only causal reasoning is possible, even if mechanisms of self-organisation are taken into account. As soon as external knowledge, i.e. information, is required, possibly in the form of creativity (of an external mind), the system is no more a closed one.

Remark: The Turing Test, which is agreed on to be the fundamental test for an Artificial Intelligence, simply compares the machine to the human mind conducting a lengthy discussion. Besides simple characteristics like response time, which comes down to computing-power, it is merely the capability to answer questions in a way a human being considers an equal counterpart. It is not a competition and can principally not state superiority over the human mind.

5. The Construction Management Situation

On this background the question arises, to which degree the operation of construction processes, i.e. construction management, is bound and completely determined by available rules and information [16]. With scheduling, all boundary conditions, as there are activities, relationships and fixed dates are given. The task remains to find an optimal solution to the minimizing problem of the construction time while obeying all the predefined conditions, which is just an ordinary well-understood task [14, 22, 23]. So far, the problem can be separated into two independent segments. First, the situation needs to be described completely and accurately before, secondly, any mechanism may approach the optimization problem. The later is certainly – difficult or simple – a matter of causal reasoning, probably minimizing losses including soft facts like fuzzy variables or probabilities, and thus may be subjected to artificial or human intelligence without violating major principles as the generation of entropy. However, the major task would be to describe the situation accordingly. Mathematical completeness is not feasible, so it comes down to judging the relevant issues to be modelled. This again may be subjected to causal reasoning as well, but on the background of individual large and complex projects seems not possible and therefore again becomes decidedly a matter of a creative mind.

5.1. Database

One of the most popular applications of Artificial Intelligence is the IBM-Watson portal. The functionality of Watson [23] describes very well the capability of AI, based on neuronal networks. In principle, the “Watson” – intelligence rests on a vast variety of unstructured data, available by the internet, as are reports, tweets, messages and other entries. The main capability is to operate on this raw data via less tight semantic analysis processes, in contrast to the exact investigation of a classical search algorithm bound to logical strictness. Therefore, a huge amount of internet data of all sorts can be made use of. The same semantic approach applies for the questions to be asked and the provided answers to additionally learn from. However, there is a point made, that internet data are not necessarily correct or relevant. To repair this, the help of a human operator is still required when acquiring data to manually sort out erroneous or insignificant information.

For Construction Management, first of all, the Building Information Model (BIM) as a presumably complete representation of the building to be erected is available [3]. The model is created as a highly sophisticated form of planning, i.e. in three dimensions, as physical objects including all of their physical and logical interactions. This is, by the way, treated and assumed to be a strict and logical model, which needs to be failure-free and complete. As soon as Construction Management comes into play, these physical elements are to be realized and processed on a time axis, optimizing project duration and cost without giving up the quality defined as perfect match to the contracts. Yet, since projects are unique, there are no criteria available whether these procedures will be or have been carried out with optimal efficiency or not. The knowledge of performing well in this respect is obviously not that strict, as present projects are teaching. Otherwise, classical algorithms like CPM, Ford etc., would be solving the given task on a mathematical basis fairly well [8, 22]. Explicitly, the particular elements of a model representing managerial issues, like detailed contracts, sub-target dates etc., as well as their organisational interaction are subject to *in-situ* coordination and therefore principally not available. The laborious and extensive task of coordination itself is defined as a costly service to be delivered during the execution of the project and therefore an element of the model which principally cannot be determined *a priori*. Thus, exactly the badly required part of the construction management model is not available within the BIM [9].

5.2. Information

The database for this fuzzy knowledge seems to suffer from some difficulties. Absolutely no significant information, neither regarding positive nor negative experience, is publicly available on the net. Knowledge of this kind (experience) is treated as specific asset (Know-how) of the companies and therefore deliberately never published. Thus, the existing knowledge is available only within the companies and therefore principally limited in volume. Furthermore, management knowledge is sourced basically on finished projects of the company and on people, i.e. on their specific education. This again is derived from abstract experience, i.e. academic examples, and structured knowledge as of how to treat situations in a more abstract way via methodical approaches. Both these sources of knowledge are not documented but bound to the respective persons as Human Capital. Thus, none of this is principally accessible for analysis by a neuronal network.

Remark: Beyond this well-reasoned situation, further experience worsening the situation is observed and reported by many participants: According to numerous investigations for expertise requests, even the experienced knowledge taken from closed projects is obviously not documented, neither in a structured way nor as unstructured data. Otherwise, according to principles of knowledge management rules the respective projects would not have been running into problems, where an expertise is required. Furthermore, people with this type of knowledge are in particular project managers and construction supervisors, who are to solve the actual problems with higher priority than to secure the knowledge for later projects. However, the coordination part of project management is mainly acting quickly on upcoming situations, leading in many cases to more intuitive reactions and not so much to data-based decision-making. Finally, the failure–culture plays a significant role. The knowledge needs to be derived from well-handled projects as well as from well understood failures.

In order to investigate the emergent behaviour via a neuronal network we observe a statistical problem: There are no two projects similar enough to form a database, where emergent behaviour can be investigated from. Statistical considerations [30] are strictly limiting the exploitability of data with no exception to neuronal networks. Significance is measured in multiples of the standard deviation which needs to be increased by factors according to sample-size based on the Student-t-distribution. Therefrom, a minimum sample-size of the order of 10^2 is required for reliable conclusions. Since the sample-size refers to projects or situations of comparable type, the number of indistinguishable classes needs to be fairly low. However, since parameters of construction management are legion, merely no two projects are really to be judged comparable. For a virtual set of e.g. 10 parameters, which are far too few, with 5 options (also far too low) each, the number of incomparable situations would already rise to more than $5^{10} = 10^7$. Thus, extracting reliable information from raw data of closed projects would require millions of projects in any case, which are available under no circumstances.

5.3. Organization

Since it is principally not possible to derive intelligence from experience, the solution is given by breaking up complex projects exhibiting starkly emergent behaviour [12, 17, 22, 24] into a number of smaller units, which are becoming less specific and therefore more general – and less complex. Therewith, both the availability of matching samples is strongly rising as well as the applicability is increasing. However needs to be taken care of, that the concatenation of these sub-elements is kept simple and linear, and therewith does not recreate a complex system of simple sub-systems. This is elaborated in [30] on the basis of Systems Theory [1, 12, 15, 25] and leads to the demand towards expertise to break up complex systems into just complicated systems, which are solely formed by the well-known graph-theoretical tree structures or rank-sorted network plans. In particular, exactly this competency is taught to managers as the central methodical approach to solve difficult, i.e. complex (non-standardisable local) construction situations based on fundamental knowledge [10]. Setting up an organization is to develop complex behaviour into complicated behaviour, i.e. investigate separability. The German Standard DIN 89901 defines a specific organisation as a central characteristic of unique projects [6]. Creating a specific organisation precisely corresponds to breaking up complexity into a well structured, i.e. linearly concatenating set of sub-units allowing to be treated separately and thus forming a frame to solve the over-all problem. This is accomplished in two steps: First, based on separability the structure of the organisation (Organisation Planning) is created and second, exactly the so established organisation coordinates and maintains the separation in detail and on the fly (Operation of Organisation) [29, 31].

The fundamental precondition to this process is the total knowledge of complexity implying the judgement of interactions between absolutely each element including the therefrom derived consequences. This would only be accessible to AI (or other Intelligence) if the systems were described and, thus, describable down to very last detail. However, this information is principally not available *a priori*. This situation would provide the conclusion of a fundamentally non-solvable problem, if the system were therefore not *created* respectively laid down based on the understanding of separability: Since an organization is specific to a project, it can not be existing *a priori* but needs to be generated based on the specific situation, be it in advance or during the operation. Since elements and interactions are also not accessible *a priori*, they need to be developed along and on the basis of general structures. These are termed "views" since they maintain only a small section of the total system, but can be understood, i.e. "overviewed" by the (human) person creating the elements or interrelations to be attached next. The structures need therefore to be simple and clear, again solely referring to graph-theoretical trees and rank-able network plans. The total system is modelled via a possibly large number of different views, maintaining different interwoven substructures and aspects. Therefore, only understood interactions are being modelled, irrelevant interactions and elements are omitted. There is naturally no prove for completeness existing. Thus, we have less of a task to actively separate existing complex systems into complicated systems, but of generating - compatible with the human mind - the description of a complex system on the basis of separability.

This process exactly represents the contribution of the human mind to the AI process. However, under the given circumstances in Construction Management, this human contribution seems to be the major part. After having completed the preparation, the remaining task can in fact be easily assigned to algorithmic means as are common.

6. Conclusion

From the market-situation it seems to be difficult to solve the task of an efficient organisation of construction (Service) based on human intelligence. This is apparently owed to the fact, that the behaviour of a project organisation exhibits clearly complex emergent behaviour and can therefore not be easily predicted by the definition of local rules. On this background, application of artificial intelligence over human intelligence suffers from some principle problems: The already used and well-established imperative and object-oriented approaches are covering all the areas where clear rules can be established, e.g. based on BIM including Operative BIM, where cost and time are implemented as higher dimensions. However, this is limited to the factually and contractually predetermined and fixed hard facts. The situation changes as soon as it comes to the service of organization, comprising *coordination* means to efficiently distribute information and *motivation* as in distributing incentives, e.g. via contracting [20]. In this context local valid rules are not available, leading to clear miss in applying imperative or object-oriented methods. The attempt to make use of neuronal networks to elaborate such rules in a less distinctive way suffers from the lack of widely available data as they are not published. On company-level available information is much too limited in volume to provide statistically significant results. Breaking down the complex situations to be tackled into smaller separable sub-tasks allows for increase of generality of the situations and therewith the universe increases as well. Taking furthermore into account, that those generalized situations are no more specific for a particular company and thus may be published, the database becomes serious. However, this is already done to a very far extent leading to the present situation, where no artificial intelligence is required to derive valid rules but well-parameterized information are available. Thus, the only remaining difficult task is the beforehand provision of the separated complex systems as a number of less complex subsystems, which serves as a precondition to any manual or algorithmical processing, setting up the specific organisation. However, precisely this preparatory task can principally not be handed to AI, but the methodical processes to generate these well-separated structures are taught with Construction Management as a specific competence by universities. Therefrom we conclude the general need for understanding organization as well-separated structures, answering the transformation of complex situations into just complicated tasks in order to determine the range of AI, i.e. algorithmical, support to this principally human task of understanding a situation and forming a model of it, which inherently implies the solvability.

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Barriers to knowledge management in small and medium construction companies in South Africa

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Abstract

Small and medium enterprises (SMEs) within the construction industry have been described to be falling short in the adoption of several management practices that could help improve their service delivery and subsequent growth within the industry. Thus, this study set out to determine the various factors that could serve as barriers towards achieving proper knowledge management (KM) within these construction organisations. The study adopted a quantitative approach through the use of a questionnaire survey carried out among staff members and stakeholders in management positions of Grade 1 to 3 general building organisations within the Johannesburg region of South Africa. Data gathered were analysed using percentage and factor analysis. The reliability of the research instrument was also tested using Cronbach alpha test while the factorability of the data gathered was tested using the Kaiser-Meyer-Olkin measure of sampling adequacy and Bartlett's Test of Sphericity. The result revealed that the barriers to proper KM practices among SMEs in the study area can be categorised under the following: people related issues, SMEs organisational issues, and project demand issues. It is believed that the findings of this study will go a long way in assisting SME's owners in managing knowledge within their organisation by avoiding certain factors that could hinder effective KM.

Keywords: Barriers; Knowledge management; Organisation management; Project management; Small and medium companies.

1. Introduction

The construction industry is a dynamic sector of ever-changing design developments posed by various design teams. It has been observed that companies put greater emphasis on constructing the final product than focusing on planning the contract program [1]. In doing this, project participants are appointed based on their expertise and background knowledge on the current work to be undertaken [2]. Despite this, most projects experience setbacks due to ineffective planning during their early stage [3]. A major set of construction companies faced with this challenge are the small and medium enterprises (SMEs). Although these construction companies have been described as the key drivers of economic growth [4], their activities and productivity are laden with problems such as poor project planning and ineffective management [5]. A crucial aspect is that of proper management of knowledge acquired within the organisation.

Most SME's are operated by owners who hardly have good background knowledge in the industry. These owners in most cases hope that their employees (experienced or not) will fill in this knowledge gap [6]. Unfortunately, it has been noted that stakeholders of the construction industry find it hard to share knowledge within an organisation. World

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Economic Forum [1] observed that institutional memory is not being conveyed equally between the stakeholders of the construction industry. Engineers and other construction experts have become organisation’s asset with the domain knowledge, and unfortunately, they tend to leave little or no knowledge at all behind for future projects when they eventually exit the organisation [7]. Civi [8] noted that stakeholders of any organisation are the originators and developers of knowledge through which a cumulative bank of knowledge that over time creates the process of the entire organisation is achieved. Therefore, organisations need to find a way in which they can manage this knowledge. According to Nakamori [9], through prehistoric knowledge, stakeholders of a company (SMEs inclusive) can solve challenges they are faced with at any particular time and can be creative to innovate and develop new ideas. Linde [10] therefore suggested that empowering stakeholders with what they need to know and allowing them a fair opportunity to express their opinions which is usually based on experience allows for the transfer of knowledge. Thus, it is not gainsaying that proper knowledge management (KM) is crucial for the growth and survival of SMEs within the construction industry considering the competitive nature of the industry. Robinson *et al.* [11] have earlier noted that KM helps create an enabling environment for the creation, storage and transfer of knowledge within an organisation.

Based on the above, this study assessed the barriers of KM in small and medium construction companies in South Africa with a view towards increasing the adoption of KM practices within SMEs in the construction industry and by extension improves their service delivery. Subsequent parts of this paper present the review of related literature, the methodology adopted for the study, the findings and conclusion. Based on the conclusion, recommendations were given.

2. Literature Review

Organisations in various sectors operate based on the knowledge individuals have gained over years of experiences in a particular field [12]. Knowledge is a resource in its self, which defines the modes and routes an organisation applies to its operational processes [8]. KM helps organisations in creating a working space where knowledge can be created, stored and transferred within the organisation [11]. Linde [8] stated that knowledge comes in two forms which are explicit and tacit knowledge. The explicit knowledge is widely accessible through the means of books and media, while the tacit knowledge is not visible and precise, thus, making it difficult to create, organise and transfer it to someone else. However, the latter is the type of knowledge that plays a major role in having the competitive advantage against other organisations through which organisations are able to tackle any challenge they are faced with [7, 13].

It has been established that organisations in developing countries are not as efficient as those countries in the developed countries. Due to tense socio-economic factors, stakeholders from both formal and informal organisations have a tendency to unconsciously reducing their productiveness [14]. Hence it is important to work within the current culture of an organisation as they are enduring the impact of cultural diversity. Organisations should rather change the behaviours of the stakeholders to improve current flaws within the organisation [15]. As the organisation improves its flaws and knowledge is being transferred between stakeholders, the entire organisation begins to improve its performance [16]. Constant sharing of knowledge will ensure that the organisation propels its self to improve on its errors, which will reduce costs and save time. It is important that an organisation understands and values knowing precisely what the clients want for their projects. The organisation may be motivated to come up with new management techniques, processes and convenient work methods which will promote growth and expansion for the organisation and meet the client’s needs [17].

Despite the advantage proposed by proper KM within organisations, most construction organisations are still falling short in the proper management of knowledge and this is evident in their service delivery. Some peculiar factors seem to be affecting the adoption of proper KM practices among construction organisations, particularly with SMEs. Herrington *et al.* [18] reported that most SME’s do not have a good financial history and are unable to create a viable business plan which make it difficult for them acquire funding from financial institutions. It gets even more difficult for SME’s to ascertain funding as the interest rate is continuously increasing making it even more difficult for them to survive the competitive environment. The implementation of advanced KM practices tends to be costly for most small and medium construction organisations as they need to start out from basic KM systems and gradually recycle these into advanced systems which help organisations to reach their full potential [19, 20, 21]. It has also been observed that most SME's cannot afford to hire professional stakeholders. This has resulted to them hiring family members who do not have the adequate knowledge and skills of the construction industry [22]. The CIDB [12] further affirmed this by stating that most owners of small and medium construction organisations run it themselves and have vague construction knowledge. This makes it even harder for them to understand the principles of running such an organisation.

Budget constraints reduce the capabilities of an organisation to invest their money in keeping their employees upskilled and in the know of currently existing knowledge in the market. Depending on the owner's willingness to share knowledge and keep the employees motivated, budget constraints may limit the promotions, rewarding structures which could have kept employees motivated, leading them to a reluctant approach in sharing knowledge [23]. There is a vast amount of literature that proves that stakeholders have limited time to share knowledge within organisations. Although they may be willing to share knowledge, they are often under pressure as projects have time constraints which do not allow for such cultures activities to occur [21, 24, 25]. This limits the absorption and growth of both the individual and the organisation. This lack of time to share knowledge also impedes organisation's ability to audit and debrief the current knowledge the organisation has attained during a project's lifecycle [25]. It has earlier been suggested that adequate time should be created so that management within an organisation can constantly check on the knowledge they have acquired. Through this, they can also decide on what best suits the core objectives of the organisation and if it requires advancement they can decide on what practices to employ to achieve this [16, 22].

3. Research Methodology

In assessing the barriers of KM in small and medium construction companies in South Africa a survey approach was adopted. The survey was conducted within the greater Johannesburg region, targeting relevant stakeholders who worked for SMEs with a CIDB grading between 1 and 3 in General Building. Management and staff members of SMEs within the study area were sampled based on their willingness to participate in the survey and by the virtue of their construction experience. The greater Johannesburg region was selected as the study area due to the high concentration of construction organisations within the area and the availability of construction projects within the city and surrounding regions. A structured questionnaire based on findings from the review of literature was adopted as the instrument for data collection. The choice of a questionnaire survey is premised on the fact that the questionnaire has been adjudged to be easiest and most widely used research instrument in most social researches and it has the ability to cover a wide range of respondents [26, 27]. A total of 80 questionnaires were conveniently distributed with 53 retrieved and found fit for data analysis. The questionnaire used was designed in sections with the first section geared towards gathering information on the respondent's background. The second section sort answers regarding the barriers of KM in small and medium construction companies in South Africa. Respondents were provided with a list of barriers identified from literature to rate based on their level of significance. A Likert scale of 1 to 5 was employed, with 5 being very high, 4 being high, 3 being average, 2 being low and 1 being very low. Data analyses were done using percentage for data on the background information of the respondents. Factor Analysis was conducted on the data gathered on the barriers of KM in small and medium construction companies. The reliability of the questions in this second section was tested using Cronbach's alpha test which gave an alpha value of 0.915, thus implying high reliability of the questionnaire used.

4. Results and Discussion

4.1 Background information

The result on the background information of the respondents revealed that 2% of the respondents had no formal qualification, 9% had a Grade 9 qualification, 28% had a Grade 12, 38% had a diploma, and 23% had a bachelor's degree. Out of these qualifications, the result further revealed that only 65% were related to construction, with 35% not related. In terms of their position within the organisation, the result revealed that 21% of the respondents were the owners, 4% were quantity surveyors within the SMEs, 30% were construction managers, and 45% were the foremen/supervisors. The respondents' years of experience within the construction sector was also assessed and result revealed that 17% of respondents have between 1 to 3 years of experience, 30% have 4 to 6 years, 25% have 7 to 10 years, and 28% have 11or more experience in the construction industry. Most (43%) of these respondents work in an organisation that is eligible to handle projects between R0 to R200,000, while 15% and 42% work within organisations that handle between R200, 000 to R650, 000 and R650,000 – R2million. Based on the result, it can be deduced that although the qualification level of workers within the assessed SMEs is somewhat low, their level of experience within the industry is high enough to give considerable answers to the research question base on experience.

4.2 Barriers of KM in small and medium construction companies in South Africa

In determining the barriers of KM in small and medium construction companies in South Africa, 13 key barriers were identified from the review of literature and presented to the respondents to rate according to their level of significance. Considering the fact that there is the likelihood of some of the identified barriers having similar underlying effects, factor analysis (FA) was deemed necessary to further group these barriers into a smaller number of coherent subscales. Although there have been several disparities as regards the ideal size of a sample for FA to be conducted, Preacher and MacCallum [28] suggested that as long as the communalities are high, and the expected number of factors is small, lesser consideration should be placed on sample size. Zhao [29] suggested communalities of 0.6 and above as being suitable irrespective of the sample size being adopted. The result from the communalities analysis revealed that all the assessed variables have communalities figure above 0.6. The result in Table 1 shows the Kaiser–Meyer–Olkin (KMO) measure of sampling adequacy and Bartlett's test of sphericity which were also used to ascertain the factorability of the data gathered. The result of the KMO test gave a value of 0.778 and a significant level of 0.000 for Bartlett's test which revealed that the use of FA for the data gathered is appropriate.

Table 1: Result of Kaiser–Meyer–Olkin and Bartlett's test

Kaiser-Meyer-Olkin Measure of Sampling Adequacy		0.827
Bartlett's Test of Sphericity	Approx. Chi-Square	495.881
	df	78
	Sig.	0.000

Conducting FA using principal component analysis (PCA) with varimax rotation, 3 components with eigenvalues greater than 1 were extracted with 0.50 set as the cut-off point for the factor loading. The final statistics of the PCA and the components extracted accounted for approximately 75% of the total cumulative variance. A look at the scree plot in figure 1 further confirms this extraction as clear elbow can be seen from the third component above. The 3 extracted factors and their variables are shown in Table 2.

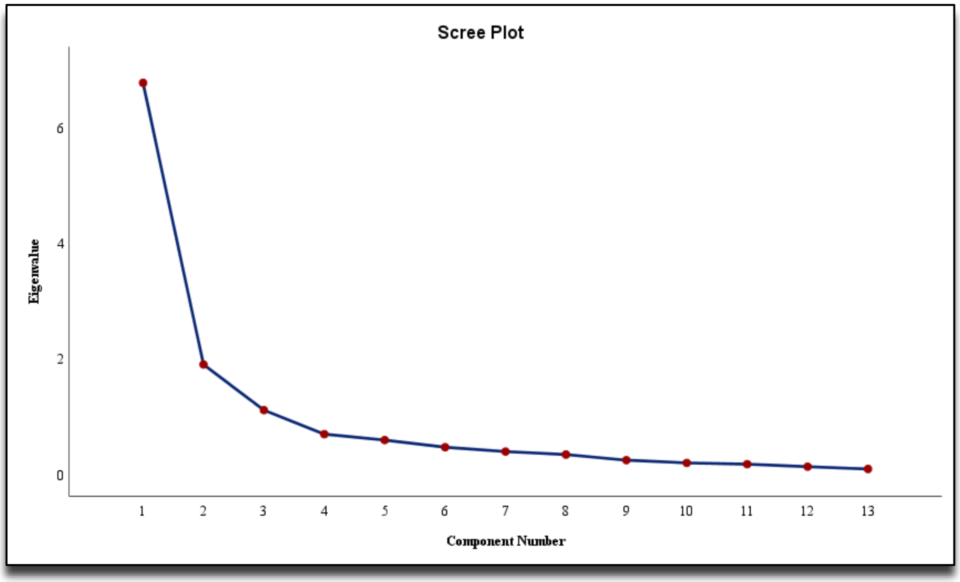

Figure 1: Scree plot

Table2: Rotated Component Matrix

Barriers	Component 1	2	3
Owner's/management's inability willingness to share knowledge	0.808		
Owners lack construction knowledge	0.791		
Unknowledgeable labour force	0.758		
Lack of research and innovation	0.710		
Inability to implement educational/upskill training programs	0.671		
Inability to hire experts		0.870	
Lack of resources		0.809	
Difficulty in getting funds		0.731	
Expensive IT systems		0.660	
Lack of projects strategic planning		0.591	
Limited time to share knowledge due to projects demands			0.897
Lack of debriefing analysis			0.803
Lack of rewards and recognition			0.707

Extraction Method: Principal Component Analysis.
Rotation Method: Varimax with Kaiser Normalization.

4.3 Discussion of Extracted Factors

a. People related issues

The first principal component has a factor loading of 5 variables and it accounts for 52% of the total variance explained. This percentage is higher than the percentage for the remaining two extracted factors combined. This means that variables loading on this component are key barriers of KM in small and medium construction companies in the study area. These barriers are; owner's/management's inability willingness to share knowledge, owners lack construction knowledge, unknowledgeable labour force, lack of research and innovation, and inability to implement educational/upskill training programs. Based on the latent properties of these variables, this component was named the

"People related issues". There is no gainsaying that being knowledgeable in construction activities is important so as to be able to impact such knowledge on others. This is important in knowledge transfer. At the same time, the willingness to transfer acquired knowledge is key if organisations are to improve in terms of their wealth of knowledge. However, the result has revealed that SMEs fall short in these areas and also in terms of upskill training programs for workers to attain the required knowledge. This result is in line with the submissions of Thwala and Mvubu [5] which noted that most SMEs in the construction industry is characterised with inadequate professional knowledge. In a similar vein, the problem of upskilling of employee's potentials and knowledge through training has been associated with poor financial standing and lack of budget allocated to same [23]. Therefore, if SMEs are to acquire, retain and transfer knowledge conveniently, factors relating to the people within the organisations and their attitude towards proper KM should be given considerable attention.

b. SME's organisational issues

The second principal component has a factor loading of 5 variables and it accounts for only 14.5% of the total variance explained. The variables loading on this component are; inability to hire experts, lack of resources, difficulty in getting funds, expensive IT systems, and lack of projects strategic planning. These variables all relate to shortcomings within SMEs itself. This is component is named "SME's organisational issues". Issues affecting SMEs are bound to limit their ability to adopt KM practices effectively. SMEs have been characterised with challenges such as lack of access to financial funding due to a prolonged recession which limits their leveraging capabilities and lack of access to markets [30]. This finance issue affects their ability to employ the right set of workers and also train the available one as observed by [22, 23]. Thwala and Mvubu [5] have earlier noted that issues such as the absence of suitable application of scientific knowledge, poor management and business control, lack of practical scientific skills, and poor resource control. All these are issues emanating from the running of these small and medium organisations and they tend to affect the proper management of knowledge.

c. Project demand issues

The last extracted component account for only 8.5% of the total variance explained and has 3 variables loading on it. These variables include; limited time to share knowledge due to projects demands, lack of debriefing analysis, and lack of rewards and recognition. This component was subsequently named "project demand issues". Construction projects are time-consuming with construction participants having little or no time to prepare for new projects in most cases. This limited time tends to affect the transfer of knowledge from one project to another and even among project participants. While participants may have the true intention of sharing knowledge, they are in most cases constrained by time to achieve this. This finding is in line with the submissions of [24] and [25]. Therefore, if construction SMEs are to improve in their service delivery and gain better competitiveness through proper management of their knowledge, then more time need to be created in achieving this feat as suggested by [16] and [22].

5. Conclusion

The study assessed the barriers of KM in small and medium construction companies in South Africa through a quantitative approach with data gathered from staff members and stakeholders in management positions of Grade 1 to 3 General Building organisations within the Johannesburg region of South Africa. Based on the findings of the study, it is, therefore, concluded the key barriers of KM in SMEs are mostly people related issues, SMEs organisational issues, and project demand issues. If SMEs within the South African construction industry is to improve their service delivery through proper KM, there is the need to improve their human capital. Gaining proper construction knowledge through proper training of their labour force, and being willing to transfer this knowledge gained is imperative. Similarly, proper management of organisational issues such as hiring the right experts within the organisation, and having the right project strategic planning will help in the proper adoption of KM practices. Also, creating more time for knowledge transfer is necessary. Adequate debriefing after each project and proper planning towards new ones based on lessons learnt from previous projects is necessary.

Although this study contributes to the body of knowledge by bringing to light of the key barriers of KM in small and medium construction companies, care must be taken in generalising the result of the study due to some identified limitations. The study was limited to a single province within the country, thus, there is a need for further studies in other provinces within the country, in order to compare results. There is also the need for further studies conducted with a much larger sample size than what is obtainable in this current study.

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Comparison of Key Project Performance Indicators of Different Construction Sectors in Terms of Collaboration and Integration

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Abstract

There is strong evidence to suggest that the use of collaboration and integration principles and methods improve overall project performance in the construction industry. Commercial Integrated Project Delivery (IPD) and Civil Infrastructure Alliance Contracting have specific collaboration and integration principles that define each as a unique delivery method. This paper investigates the similarities and differences between IPD and alliancing in terms of their key principles and explains the differences using the inherent differences between the construction sectors that have dominantly used each of the project delivery methods. The study uses 14 key performance indicators that are typically used to measure the performance of construction projects categorized into a) design optimization and b) construction risk management. The study concludes that IPD is more preferable for projects that require design optimization as the major KPI while alliancing might be more suitable for projects that deal with a significant amount of construction risks. The findings of this study can serve as a guide to properly identify collaboration and integration principles that will allow for better and enhanced project performance in a specific construction sector.

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Keywords: Integrated project delivery; alliance contracting; integration and collaboration; project performance; project delivery method.

1. Introduction

The traditional approach to deliver projects using design-bid-build transactional contracting methods intentionally separates designers from construction contractors in order to maintain checks and balances [1]. In doing so, it limits opportunities for team collaboration and integration to bring the best value to the project and often creates adversarial environments leading to claims, disputes, and delays. Due to this, owners have turned to alternative delivery methods integrating design and construction with the objective of reallocating risks among project stakeholders and increasing the collaboration among project teams. The recent appearance of relational project delivery arrangements (Integrated Project Delivery (IPD) and Alliance Contracting (Alliancing)) represents a paradigm shift as they entail risk sharing rather than risk transfer, taking project team collaboration and integration to a higher level.

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The commercial construction sector in the U.S., specifically the health care facilities sector, has seen successful implementation of the IPD approach over the past decade. IPD is considered a structured, but flexible project delivery arrangement that promotes and enhances team collaboration and work process integration. IPD is a project delivery approach that integrates people, systems, business structures, and practices into a collaborative process to optimize results and increase value of the project by maximizing efficiency through all phases of design, fabrication, and construction [2]. While IPD is still an evolving concept, it comprises a broad spectrum of project delivery strategies, methods and tools that fundamentally promote team collaboration and work process integration to achieve the best value for the project.

It is also important to note that another highly integrated project delivery method called Alliance Contracting or more commonly Alliancing has been successfully employed internationally to deliver large infrastructure and industrial projects in Europe, Australia and New Zealand. In Australia, Alliancing has become a broadly accepted procurement and delivery method for risky and complex projects. Philosophically and conceptually, Alliancing strives to achieve the same goals as IPD and both operate on a “best for project” basis where everybody wins or loses. Alliancing has performed with similar positive results as commercial IPD in a survey of 71 alliance infrastructure projects, 85% of projects met or came in under budget, and 94% of alliance projects were completed on time or ahead of schedule [3].

Even though both IPD and Alliancing aim at accomplishing the success of a project via enhanced collaboration and integration of project participants and work processes, the focal areas and strategies appear to be different as their application project types are different. IPD in the U.S. has been predominately used in the health care facilities projects and Alliancing in heavy civil projects. This study first compares the main characteristics between IPD and Alliancing and then, evaluates two categories of key project performance indicators (KPI), namely, a) Design optimization and b) risk management that are typically considered for commercial projects and civil infrastructure projects. The study concludes that both IPD and Alliancing share the philosophical common denominator but IPD focuses more on design optimization driven collaboration and integration while Alliancing is more focused on construction risk management driven strategies and methods.

2. Key Characteristics of IPD and Alliancing

IPD characteristics may be categorized as six cardinal pillars using research findings from [4],[5], and [6]. They are a) early involvement of key stakeholders, b) shared risk and reward, c) collaborative decision-making and control, d) jointly developed and validated targets, e) Liability waivers among key participants, and f) multi-party agreements. The characteristics in these six pillars are not mutually exclusive but rather highly interdependent. However, in practice, there is no consistent model accepted by the industry as a whole. “Different definitions and widely varying approaches and sophistication levels mean that the term “IPD” is used to describe significantly different contract arrangements and team processes.” [5].

Alliancing used in Australia and New Zealand relies on high levels of integration among alliance members that is thought to also produce enhanced cooperation between the individuals each member assigns to the project. The four most populous Australian states have institutionalized six main characteristics in their policy documents which include a) Early Involvement of Key Participants, b) Risk and Opportunity Sharing, c) Commitment to ‘No Disputes’, d) No fault-no blame’ culture, e) ‘Best for Project’ unanimous decision-making processes, f) Transparency expressed as open book documentation and reporting, and g) Collective sharing of project risks

2.1 Commercial IPD and Alliancing Principles used on Selected Case Study Projects

Commercial IPD and alliancing share many of the same principles such as early involvement of key parties, transparent financials, shared risk and reward, joint decision making, and a collaborative multi-party agreement” [4]. Australia has institutionalized many of these principles in government policy documents where IPD principles have been used primarily in the private sector in the US.

A content analysis was conducted of selected case study projects performed using commercial IPD in the US and alliancing in Australia or New Zealand to determine the frequency of use of these principles on actual projects. The commercial IPD case studies were building projects, with most of them being hospitals, documented in an AIA and University of Minnesota study published in 2012 [7]. The alliancing case studies were civil infrastructure projects upon which a content analysis was performed to identify the principles documented in the request for proposal (RFP), project alliancing agreement (PAA), or contract templates. The content analysis focused on the commercial IPD collaboration principles and alliancing integration principles used in each respective case study project. Table 1 depicts the percentage of each principle used on 12 commercial IPD projects, and Table 2 illustrates the percentage of each principle used on 10 alliancing projects.

Table 1 Use of IPD principles - Commercial IPD Case Study Projects (AIA 2012).

IPD Principles	Cathedral Hill	Mercy Master Plan	Lawrence & Schiller	Spawglass Austin	Edith Green Wendell	Autodesk	Sutter Health	Cardinal Glennon Childrens Hospital	St. Clare Health	Encircle Health	Walter Cronkite School of Journalism	UCFS Mission Bay	**Total Frequency**
Jointly Developed and Validated Targets	X	X	X	X		X	X			X	X	X	**75%**
Early Involvement of Key Participants	X	X	X	X	X	X	X		X	X	X	X	**92%**
Collaborative Decision-making and control	X	X	X	X	X	X	X	X	X	X	X	X	**100%**
Shared Risk and Reward		X		X	X	X	X			X			**50%**
Multi-party Agreements	X	X	X	X		X	X	X	X	X			**75%**
Liability waivers among key participants	X			X		X							**25%**

Table 2 Use of Alliancing Principles - Civil Infrastructure Alliancing Case Study Projects

Alliance Principles	Robinson Road	Southland Alliance	Jialan Yard Upgrade	Northern Missing Link	Transit NZ	Waikato Roads	Whanganui Road	Australian Government	SCIRT Alliance	NCTIR Alliance	**Total Frequency**
Early Involvement of Key Participants	X	X	X	X	X	X	X		X	X	**90%**
'Best for Project' Unanimous Decision Making	X	X	X	X	X	X	X	X	X	X	**100%**
Transparency expressed as open book documentation	X	X	X	X	X	X	X	X	X	X	**100%**
Gain Share/Pain Share, Commercial Risk and Opportunity Sharing	X		X	X	X	X	X	X	X	X	**90%**
Commitment to 'No Blame' Culture, 'No Disputes'	X	X	X	X	X		X	X	X	X	**90%**
Collective Sharing of (Nearly) all Project Risks	X		X	X	X		X	X	X	X	**80%**

Due to the small number of case study projects for both IPD and Alliancing, it is premature to statistically conclude the differences in focal areas of those key characteristics for each project delivery method. However, one can see that the alliancing projects in Australia and New Zealand use a higher percentage of their defined principles than that of their commercial IPD counterparts in the US. Also, there are some distinctive differences by comparing the two Tables that "Shared risk and reward" and "liabilities waivers among key participants" are not often used in IPD projects while in Alliancing, similar characteristics such as "Gain Share/Pain Share, Commercial Risk and Opportunity Sharing," "Commitment to 'No Blame' Culture," and 'No Disputes' "collective sharing of (nearly) all project risks" are commonly used. This noticeable difference might be caused by the inherent nature of projects that each of the project delivery method is typically applied to. For instance, commercial building (health care facilities) projects may have a major project performance objective which requires design optimization to maximize the space usage for different functions and purposes of spaces. On the other hand, heavy civil infrastructure projects tend to be horizontally linear occupying a considerably large amount of land. Thus, they face a significantly large amount of risks during construction due to environmental concerns, unexpected soil considerations, issues with neighbouring businesses and communities. This hypothesis was evaluated using content analysis of previously published journal articles.

3. Comparison of KPIs in Commercial Building and Infrastructure Projects

A total of 14 project key performance indicators (KPI's) were identified through literature review of the articles that studied KPIs used in construction projects. The 14 KPI's shaping definition of success on construction projects have been observed to be cost and schedule savings, cost and schedule certainty, quality, safety, energy/water efficiency, operational functionality, material optimization, adaptability, minimize claims, minimize environmental impacts, and minimize public disruption. These 14 KPI's were divided into two main categories; project performance objectives closely related to design optimization and project performance objectives closely related to construction risk management.

The aerospace industry and NASA have been using collaborative design optimization strategies for multiple decades and often times refer to this process as multidisciplinary design optimization, or MDO [8],[9],[10]. The goal of this collaborative optimization exercise is to maximize or minimize specific design objectives. In the architecture, engineering, and construction (AEC) industry, MDO has been stated to be used "to improve product quality and reduce time to market" [11]. Some cited benefits of MDO are "22 percent *cost savings* on average…20 percent *less time*" [12], "maximize *energy efficiency*" [13], and "reducing *total project construction cost* by 7 percent" [11], "in a multidisciplinary design environment, use of the collaborative architecture provides additional *operational* advantages" [14], and "collaborative design is an emerging promising field…*optimizing the use of materials and energy* can be effectively achieved using these new technologies" [15]. The following KPI's have been identified as project performance objectives achieved through good design optimization; i)Cost savings, ii) Schedule savings, iii) Energy/water efficiency, iv) Operational Functionality, v) Adaptability, and vi) Material Optimization (Reduced waste)

Risk is defined by the US Project Management Institute (PMI) as, "an uncertain event or condition, if it occurs, has a positive or negative effect on a project objective" [16]. Project uncertainty is the probably that the objective will not reach its planned target value [17]. Construction projects face much uncertainty due to many factors, thus increasing the risk of not achieving the target value, or project performance goals and objectives. "Risk is inherently present in all construction projects…quite often, construction projects fail to achieve their *time, quality, and budget goals*" [18]. Other studies have identified similar uncertainty to achieving project performance objectives, with risks observed causing defective physical works (difficulty in *quality* control), *schedule delays*, and *cost overruns* [19] and [20] identified five main impacts to project success caused by risk; *cost overrun, time delay, quality, safety, and environmental* risks. Legal claims and disputes have also been identified by scholars as a risk present with construction projects, "construction industry professionals have increasingly sought legal assistance to help identify, allocate, control, minimize risk in the design and construction process…in spite of these efforts at controlling risk, the industry has witnessed an alarming rise in *claims and disputes*." [21] "The construction industry has long been considered to have high injury and fatality rates" Cheng et al.[22] goes on to state, "*safety* management information and committees are significantly related to *project performance*." Social impacts of construction projects, such as public disruption, have also hampered overall achievement of project goals. Documented in a study performed by [23] of the Olympic Games development work performed in Sydney, Australia, "Personal *disruptions* impacted more heavily than any benefits. One respondent expressed displeasure with the Olympics in terms of personal *disruptions* to daily activities as follows, ‘It’s been bloody chaos, mate. It’s all bad. Nothing but [a] *disruption* to my life.’” The following KPI’s have been identified as project performance objectives achieved through good construction risk management; i) Cost Certainty (meet budget), ii) Schedule Certainty (meet schedule), iii) Safety, iv) Quality, v) Minimize Claims, vi) Minimize Environmental Impacts, vii) Minimize Public Disruption.

Client satisfaction has been observed in literature to be both related to good design optimization and good construction risk management and therefore categorized as both. There are a total of six KPIs categorized as design optimization, seven KPI’s categorized as construction risk management, and one categorized as both. The frequency index (0-100) of these total 14 KPI’s categorized as design optimization and/or construction risk management represents the frequency of literature articles observed identifying each of these specific KPI’s grouped as commercial buildings, civil infrastructure, and general construction projects and is summarized in Table 3.

Table 3 Literature review of design optimization and construction risk management KPIs

Industry Sector	Design Optimization KPI’s							Construction Risk Management KPI’s								
	Cost Savings	**Schedule Savings**	**Energy/Water Efficiency**	**Operational Functionality**	**Adaptability/Reliability**	**Material Optimization**	**Average of All Design Optimization KPI’s**	**Cost Certainty**	**Schedule Certainty**	**Safety**	**Quality**	**Minimize Claims**	**Minimize Environmental Impacts**	**Minimize Public Disruption**	**Average of all Construction Risk KPI’s**	**Client Satisfaction**
Commerical Building																
1 – Franz [1]	X	X	X	X				X	X		X					X
2 – WBDG [24]	X		X	X	X					X						
3–El Asmar [25]	X	X		X		X		X	X	X	X	X				X
4 – Roberts [26]	X	X		X				X	X	X	X		X			X
5 – Ballard [27]	X		X	X		X		X								
6 – Beach [28]	X	X		X		X		X		X		X				
7 – Chan [29]	X	X		X		X		X	X	X	X		X			X
8 – Wong [30]	X	X						X	X	X	X					
9 – Chan [31]	X	X		X		X				X						
10–Sanvido [32]	X			X	X	X		X	X	X	X	X				X
Frequency$_{Building}$	**100**	**70**	**30**	**90**	**20**	**60**	**62**	**80**	**60**	**80**	**60**	**30**	**20**	**0**	**47**	**50**
Infrastructure																
11 – Amiril [18]	X		X	X	X	X		X	X	X	X	X	X	X		X
12 – Molenaar [33]				X				X	X	X	X			X		X
13 – Zhou [34]	X			X		X					X		X	X		
14 – Shen [35]	X		X	X		X		X		X	X	X	X	X		
15 – Toor [36]						X		X	X	X	X	X				X
16 – Tamburro [3]				X				X	X	X	X	X	X	X		
17 – Rankin [37]								X	X	X	X		X			
18 – Ugwu [38]	X	X				X		X	X	X	X		X	X		
19 – Grajek [39]	X							X	X			X				
20–Gransberg [40]	X							X	X			X				
Frequency$_{Infrastructure}$	**60**	**10**	**20**	**50**	**10**	**50**	**33**	**90**	**80**	**70**	**80**	**60**	**60**	**60**	**71**	**30**

Using the average frequency of all sectors including general construction as the baseline frequency index, the results of the frequency analysis summarized in Table 3 indicate commercial building projects are higher in importance of KPI’s more closely associated with design optimization, having an average frequency index rating of 62 for all design optimization KPI’s as compared to an average frequency index rating of 43 for all sectors’ design optimization KPI’s. Cost savings and operational functionality were the two highest ranked KPI’s for commercial building projects. While civil infrastructure projects are higher in importance of KPI's more closely associated with construction risk management, having an average frequency index rating of 71 for all construction risk management KPI's as compared to an average frequency index rating of 54 for all sectors' construction risk management KPI's. Cost and schedule certainty, and quality were the three highest ranked KPI's for civil infrastructure projects. The results indicate project performance is more closely linked to design optimization for commercial projects, while civil infrastructure project performance relies more heavily on construction risk management.

4. Conclusion

This study found that there is a discernible difference between commercial projects and civil infrastructure projects regarding the relative importance of key performance indicators. Commercial project KPIs are more focused on design optimization whereas civil infrastructure project KPIs promote construction risk management. Thus, it can be inferred that commercial projects are inherently "design-centric" where critical project success factors revolve around the design solution. On the other hand, civil infrastructure projects are much larger in scale and typically impact a greater population making achieving cost and schedule certainty through "construction-centric" risk management key for project success. Both IPD and Alliancing philosophically aim at the same goal of project success through enhanced collaboration and integration. However, due to the different focal points in terms of KPIs, IPD and Alliancing tend to focus more on different collaboration and integration principles and methods. These findings are not based on statistical validation results which could be weakness and open up for future research. However, the results provide highly valuable insights. For example, another major sector in the construction industry is the industrial sector. The industrial sector may have characteristics for both commercial building and civil infrastructure projects. Industrial projects may require design optimization and construction risk minimization. Thus, if an collaboration and integration driven project delivery method is applied for an industrial project, all IPD and Alliancing principles may have to be used in a balanced manner. This is a strong hypothesis which may require future research that the research team has already started to investigate.

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Comparison of perceptions about women managers working on construction sites

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Abstract

Recently, women's social participation has increased. In Korea, the proportion of women in each field is increasing, including that involved in architecture engineering. However, most women who are engaged in construction engineering tend to avoid working on construction sites. Therefore, the proportion of women managers working on construction sites is very low. Despite these problems, there are few studies on the situation of women working on construction sites. The purpose of this study is to examine the reasons why women managers avoid working on construction sites and to compare the perception about women managers working on construction sites. By doing this, construction site organization management methods could be suggested for improving the proportion of women managers working on construction sites.

Keywords: women manager; awareness; organization; comparison; on-site working;

1. Introduction

1.1. Background and purpose

The participation of women in society is growing worldwide. However, women's social participation in Korea is lower than in Western societies [1]. In particular, the proportion of women is significantly lower in the construction industry where traditionally women's participation has been low. According to the data published on May 28 [2], 2018 by the Korea Economic Research Institute, the proportion of women workers in top 600 listed companies (excluding finance and insurance companies) is 23.7%, but the proportion of women workers in the construction industry is 9.5%, which is the lowest among all industries.

The construction industry is aware of this problem and is continuously making efforts to increase the proportion of women workers. Nevertheless, the proportion of women workers in the construction industry is still very low. Among the top five construction companies, the proportion of women in the total number of regular employees in 2017 was 10.7% for Samsung C&T, 6.1% for Hyundai E&C, 8% for Daewoo E&C, 5.8% for Daelim, and 6.4% for GS E&C [3]. It seems that the gender imbalance problem is particularly difficult to solve in the construction industry.

A greater problem is that most women who majored (or are majoring) in construction continue to avoid working on construction sites. To solve this problem, we need to research the reasons why women avoid working on construction

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sites, but there are few studies on women managers working on construction sites. Therefore, this study aims to compare the perceptions of men and women on women managers working on construction sites to investigate the reasons why women managers avoid working on construction sites.

1.2. Study scope and method

The purpose of this study is to compare the perceptions of men and women on women managers at construction sites. Thus, a questionnaire survey was first conducted for men managers working on construction sites in Daegu and Gyeongsangbuk-do to examine how men perceive women managers working on construction sites. In addition, to examine the perceptions of women on women managers at construction sites, a questionnaire survey was conducted for female students who were prospective graduates in construction-related departments of universities. Information on women workers

1.3. Current status of women workers

As shown in Table 1, the number of women workers in the Korean labor market has increased, as compared to the past, and the economically active women population has increased [4]. However, even though the wages of women workers are increasing, the wage gap between men and women workers has not decreased, but rather increased (see Table 2) [5]. In other words, the gender imbalance still exists in the labor market [6].

Table 1. Changes in economically active women population and participation rate

Classification	2007	2009	2011	2013	2015
Women population over 15 (million)	20.1	20.5	21	21.5	22
Economically active women population (million)	10.1	10.1	10.4	10.8	11.4
Women's economic activity participation rate (%)	50.2	49.2	49.7	50.2	51.8

Table 2. Changes in the ratio of women's monthly salary to men's monthly salary

Classification	2011	2012	2013	2014	2015
Monthly salary of men workers (thousand KRW) (A)	2,444	2,569	2,664	2,761	2,837
Monthly salary of women workers (thousand KRW) (B)	1,548	1,654	1,705	1,742	1,781
Ratio of women's monthly salary to men's monthly salary (%) (B/A)	63.3	64.4	64	63.1	62.8

1.4. Characteristics of work places preferred by women [7]

Companies with a high proportion of women workers have one characteristic in common: they operate a program for work–family balance. For example, Lotte Shopping with 68.1% women workers has a child care leave program, which allows women workers to take a leave around the time when their children enter the elementary school. They also have a restart education program to support reinstatement after the child care leave.

CJ Freshway with 57.3% women workers support the artificial insemination surgery expenses for new infertile couples without children, give presents to women workers who gave birth, and operate a child care leave program to prevent career interruptions during pregnancy and childbirth.

LG Household & Healthcare with 56.3% women workers have continuously reformed their systems and organizational culture to eliminate the male-dominated culture and gender discrimination and to establish management based on respect for women.

1.5. Special nature of construction sites and women

The construction period is crucial in the construction industry. If the construction period is delayed in public construction works, the constructor must pay liquidated damage for the delay. Thus, rush works are frequently performed to meet the construction deadline at construction sites. During rush works, the site managers must work even at night and during the weekend.

Contrary to this special nature of construction sites, women place great importance on work-hour compliance. According to the "Basic Analysis Report on Korean Education & Employment Panel" announced in November 2015 [8], the first factor on which women place the highest importance is regular work hours and the third factor is five-day workweek.

2. Comparison of perceptions on women managers at construction sites

2.1. Survey overview

To compare the perceptions of men and women on women managers at construction sites, a questionnaire survey was performed for men first. The participants were 50 men managers at construction sites in Daegu and Gyeongsangbuk-do. For women, 50 female prospective graduates in construction-related departments (construction and construction engineering departments) of the universities in Daegu and Gyeongsangbuk-do were surveyed. The survey period was from April to June in 2018.

The questionnaires were composed of large three parts. The first part was only for male participants and was related to the perception on women managers working on construction sites. The second part was related to the perception of women managers at construction sites. The third part was related to what needs to be improved for work on construction sites. The second and third parts were for both men and women.

2.2. Perceptions of men managers on women managers at construction sites

Among the 50 men managers surveyed, only 16% had experience working with women managers at construction sites. Regardless of their experience of working with women managers at construction sites, most of the male managers were positive about women managers at construction sites (see Fig. 1). However, most of them said that the proportion of women managers at construction sites is not increasing, as shown in Fig. 2.

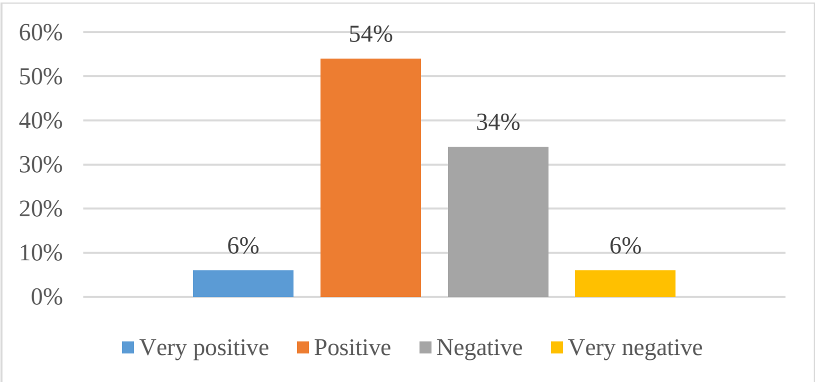

Fig. 1. Perceptions on women managers at construction sites

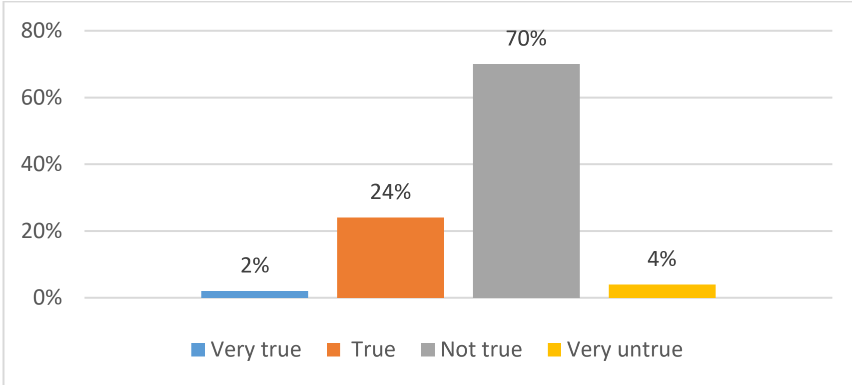

Fig. 2. Perceptions on the increase in the proportion of women managers at construction sites

2.3. Comparison of perceptions on women managers at construction sites

Regarding the advantages of working on construction sites, both men and women chose high salary as the first advantage. Men chose "active" and women chose "career-based treatment" as the second advantage. This shows that there are differences between men and women in perceptions on the advantages of working on construction sites. Regarding disadvantages of working on construction sites, men chose "irregular work on holidays" and women chose "gender discrimination" as the first disadvantage. This shows that there are differences between men and women in perceptions on the disadvantages of working on construction sites, as well.

Regarding the advantages of women managers at construction sites, there were large differences between men and women in perceptions on the learning ability and job performance ability, as shown in Fig. 3. Men considered learning ability as an advantage of women managers, whereas women considered job performance ability as an advantage. Furthermore, regarding the disadvantages of women managers at construction sites, both men and women chose lack of confidence as the first disadvantage, as shown in Fig. 4. However, clear differences appeared between the perceptions of men and women regarding responsibility and communication ability. Men considered lack of responsibility as a disadvantage of women managers at construction sites, whereas women considered lack of communication ability as a disadvantage of women managers at construction sites.

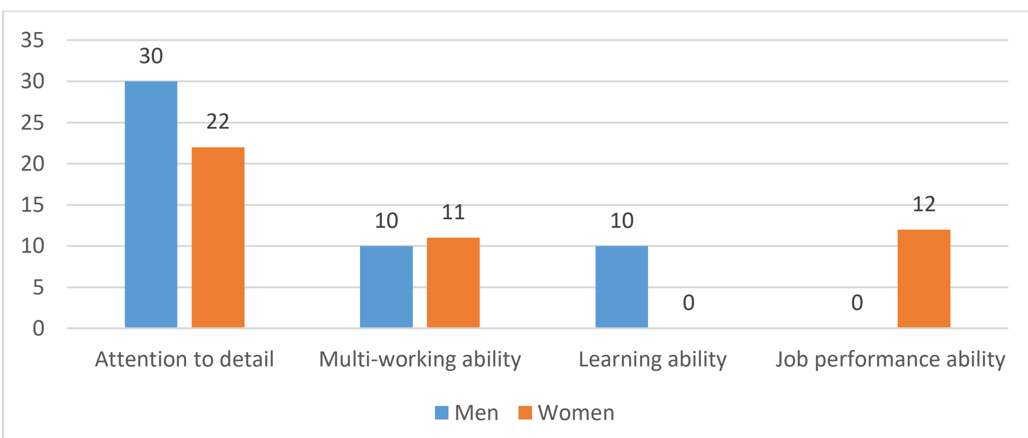

Fig. 3. Advantages of women managers at construction sites

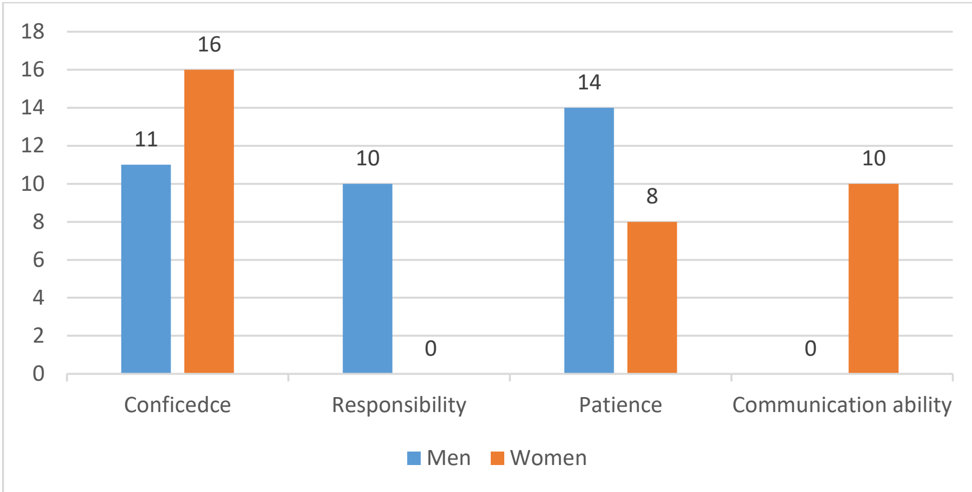

Fig. 4. Disadvantages of women managers at construction sites

2.4. Measures to improve preferences for working on construction sites

We surveyed what needs to be improved to improve women managers' preference for working on construction sites. Men placed the highest priority on changing women's attitude of avoiding working on construction sites and improvement of working conditions, whereas women placed the highest priority on the improvement of the situation of gender discrimination at construction sites.

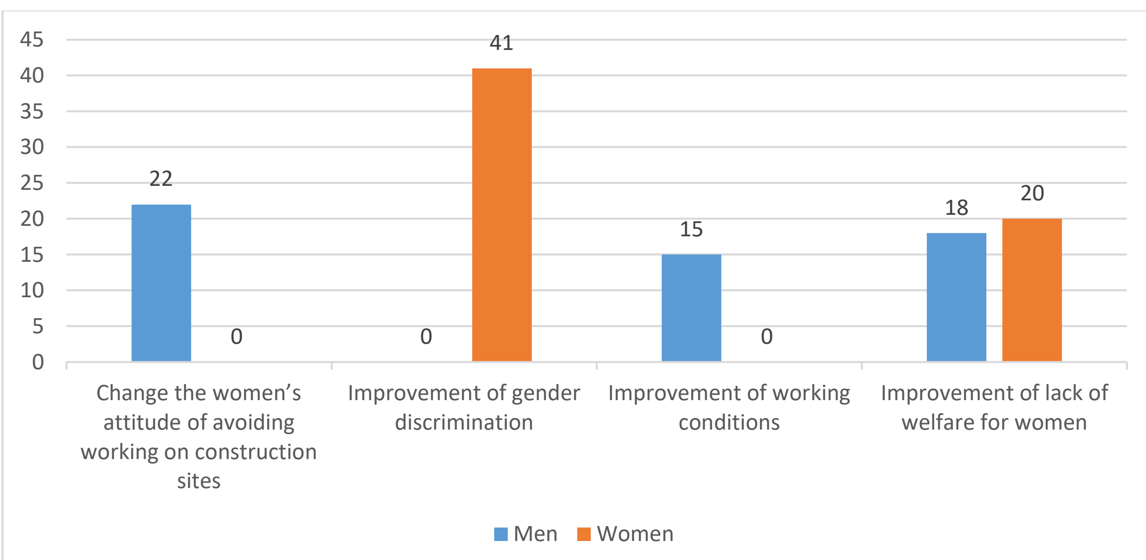

Fig. 5. Improvement measures

3. Conclusions

Men managers and female prospective graduates of construction-related departments were surveyed to compare perceptions of men and women on women managers at construction sites. The survey results show that both men and women are positive about women managers at construction sites. However, the surveyed men and women showed differences in their perceptions on the advantages and disadvantages of women managers at construction sites. Women regarded multiprocessing ability as an advantage of women managers, whereas men regarded learning ability as an advantage of women managers. As for disadvantages, women regarded lack of communication ability as a disadvantage of women managers, whereas men regraded lack of responsibility as a disadvantage of women managers.

Men and women also showed large differences in their opinions about how to improve gender imbalance. Men considered that changing women's attitude of avoiding working at construction sites is important, whereas women considered that improvement of the situation of gender discrimination at construction sites is important.

To summarize the results above, men and women had different perceptions about women managers at construction sites. Therefore, the most important precondition for increasing the proportion of women managers at construction sites is to recognize the differences in perceptions between men and women.

It is difficult to apply the results of this study to all construction site managers because they were obtained from questionnaire surveys on men managers at construction sites and female prospective graduates in construction-related departments of universities. Therefore, further research on women managers is necessary in the future. The results of this study will assist construction companies in their organizational management of women managers at construction sites.

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Competitive Strategies of Thai Contractors in Construction Project Management in the CLMV Countries.

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Abstract

CLMV countries, namely Cambodia, Laos, Myanmar and Vietnam, are potential overseas markets for Thai contractors. Since the CLMV countries are in the developing stage, there are many construction and infrastructure projects emerging in order to develop economic growth of those countries. Therefore, it is an opportunity for Thai contractors to enter the CLMV construction markets. The study aims 1) to study the conditions and factors underlying in the construction business and construction project management for Thai contractors who enter the CLMV countries, and 2) to establish the competitive construction management strategies that could be adopted by Thai contractors in the CLMV countries. This study is a qualitative research. The population is divided into 2 groups, one is the senior executives of Thai contractors who manage their construction projects in Laos or Myanmar, the other is the project owners or stakeholders in construction industry of the studied nations. Data collection instruments were the interview forms and data analysis used content analysis. Research findings revealed that the construction industry in CLMV countries are still in high demand of construction projects. Strengths of Thai contractors were time and quality management while weaknesses was price management. Therefore, Thai contractors should play their roles by using differentiation strategies and niche strategies.

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Keywords: CLMV countries; competitive strategy; construction project; project management; Thai contractors.

1. Introduction

Investing in the overseas construction project is an alternative to Thai construction companies during the period of the domestic economic crisis. At the present, some of Thai construction companies have expanded their businesses to the global market especially in the CLMV countries namely Cambodia, Laos, Myanmar and Vietnam. CLMV countries are potential market for Thai construction business for not only a main contractor but also a subcontractor. Since CLMV countries are in the developing stage, construction project such as large scale infrastructure projects are still in high demand. This is an opportunity for Thai construction contractors to enter the construction market in the CLMV countries. However, the operation of construction projects in the CLMV countries has higher risks than in Thailand. Therefore, Thai contractor should establish their strategies in order to compete in the international market.

In addition to their domestic businesses, Thai construction companies, especially larger ones, are increasingly expanding their customer base into overseas' markets, in particular to the CLM (Cambodia-Laos-Myanmar) region due to these countries' rapid economic expansion and the concomitant development of their national infrastructure and built environment including, for example, road building and large-scale residential development. SMEs have the possibility of either working on smaller projects or sub-contracting for larger companies doing work such as restoration and finishing work on housing. Being able to take advantage of these openings depends on building partnerships with

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operators in the overseas' markets and developing relationships with larger Thai operators to sub-contract for or to use as a source of financing. [1]

It can be seen that the investment situation in the construction business of Thai entrepreneurs in the CLMV countries has good potential. Recently, there are a number of Thai contractors operating the construction projects in such countries. The increasing number of foreign contractors in the CLMV countries has generated wide interest in the competitive strategy in managing construction project effectively. Therefore, this study aims: 1) to study the conditions and factors underlying in the construction business and construction project management for Thai contractors who enter the CLMV countries; and 2) to establish the competitive construction management strategies that could be adopted by Thai contractors in the CLMV countries.

2. Literature Review

2.1. The concept of competitive strategy

The term of strategy is difficult to be defined and there are efforts found in many management texts to provide a clear definition. A strategy is also a set of rules for guiding decisions about organization behavior. It may be explicitly or implicitly, kept within the confines of the senior management team or pervading the organization to produce a sense of common direction. Two views have emerged on the nature of strategy. The first perspective views strategy as *planning* mode. A strategy is work out in advance, is explicit and it deals with the managers who develop a systematic and structured plan to meet objectives. The second perspective sees strategy as an *evolutionary* mode. From this viewpoint strategy evolves over time. It is not thought out and planned, but it is rather a stream of significant decisions. [2] Consequently, for the purpose of this research, strategy is defined as the determination of a basic long-term objectives and the adoption of courses of action and allocation of resources necessary to achieve the goals.

Developing a competitive strategy, a company must determine how the firm is going to compete; what its goals should be; and what policies are needed to carry out these goals. Thus, the competitive strategy of the company will be a combination of the goal for which the firm is striving, and the means by which it is seeking to get there. At a global level and beyond the articulation of a competitive strategy, two types of key factors determine the company's accomplishment: factors internal to the company and factors external to the company. [3] Internal factors can be grouped into two general areas include organization's strengths and weaknesses and personal values of an organization. While external factors can be divided into industries opportunities and threats and societal expectation.

2.2. The five competitive forces

The first fundamental determinant of a firm's profitability is industry attractiveness. Competitive strategy must grow out of a sophisticated understanding of the rules of competition that determine an industry's attractiveness. The ultimate aim of competitive strategy is to cope with and, ideally, to change those rules in the firm's favor. In any industry, whether it is domestic or international, produces a product or a service, the rules of competition are embodied in five competitive factors: the entry of new competitors, the threat of substitutes, the bargaining power of buyers, the bargaining power of suppliers, and the rivalry among the existing competitors. The five forces determine industry profitability because they influence the prices, costs, and required investment of firms in an industry.

3. Conceptual framework for research

From the review of concepts, theories, literature and related researches, this study expects to conclude the concept of competitive strategy of the contractor in managing construction projects by analysing external factors and internal factors.

External factors or demand conditions are related to competitive environment and societal environment. Competitive environment is the situation that the company must face in the organization operation, including industry competitors, threats of new entrants, bargaining power of buyers, bargaining power of suppliers, threats of substitute products or services, and stakeholder. Societal environment is beyond the business system. It depends on the current situation which affects the long-term business comprising economic, society and culture, technological and political factors.

Internal factors or production factors consists of company organizational management and human resources potential. Company organizational management include financial resources such as source of fund, financial management and construction project management technique such as integration management, scope management, time management, quality management, communication management, risk management, safety management, environment management and claim management. Human resources potential or personnel's highest capabilities was determined by motivation and characteristics of the executives.

To formulate contractor competitive strategy external factors and internal factors of Thai contractors were analysed to find out strengths, weaknesses, opportunities and threats of Thai contractors in the CLMV countries after that TOWS matrix concept has been applied to establish 4 competitive strategies, namely aggressive strategy (SO strategy), corrective strategy (WO strategy), defensive strategy (ST strategy) and proactive strategy (WT strategy). Aggressive strategy (SO strategy) is the most desirable situation of the organization that use strengths to take advantage of opportunities. Corrective strategy (WO strategy) is a situation in which the organizations use their opportunities to overcome and avoid threats. Defensive strategy (ST strategy) is a situation that arises from the environment that the organizations take advantage of their strengths to avoid real and potential threats. While proactive strategy (WT strategy) is the worst situation. The organizations are facing external threats and involving with many internal weaknesses, therefore they have to minimize their weaknesses and avoid the threats. The conceptual framework for research is shown in Fig.1.

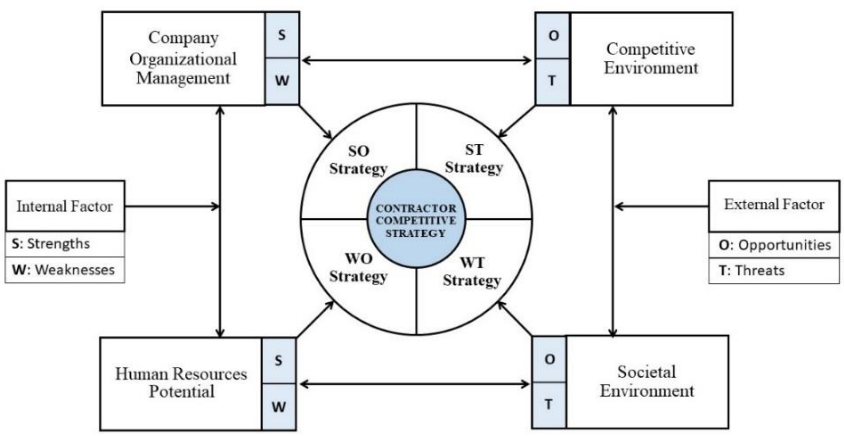

Fig. 1. Conceptual framework for research.

4. Research Methodology

This research is a qualitative research. The population is divided into 2 groups, one is the senior executives of Thai contractors who manage their construction projects in Laos or Myanmar, the other is the project owners or stakeholders in construction industry of the studied nations. The researcher collected data by using in-depth interviews. Data collection instruments were in the form of interview. Data analysis use content analysis.

5. Results and Discussion

5.1 Conditions for Thai contractors in the construction project management in the CLMV countries

Due to continuous economic growth of the CLMV countries, rapid urban development with an increasing number of construction and sub-contracting works has been emerging. As a result, CLMV countries gain significant interest from both domestic and foreign investors. In accordance with the report of the Export-Import Bank of Thailand, which states that after the Laos becomes an ASEAN member, it is an important turning point for the international trade of Laos to grow rapidly. [4] Moreover, after the general election and the establishment of a new government in Myanmar Union, the country's trade and investment become highly potential country for both trading and investment. [5] In addition, the investment promotion policies of CLMV countries also motivate Thai contractors to be interested in implementing construction projects in CLMV countries by special investment privileges.

Construction projects in Laos and Myanmar can be categorized into 2 types, private and public construction projects. The private construction projects are mostly residential buildings such as apartments, residential condominiums and commercial buildings such as hotel, shopping center, hospital, factory, etc. The public construction projects usually supporting the country's development, are infrastructure and energy projects such as dam, hydroelectric power plant, road and expressway. Either constructing those private or public ones in the CLMV countries, the contractors should examine the local building laws or regulations and the local process and procedure of building permission should be thoroughly studies.

5.2 Factors of Thai contractors in the construction project management in the CLMV countries

According to the conceptual framework of this research, there are external and internal factors that Thai construction contractors should consider when managing construction projects in the CLMV countries.

External factors

1) Competitive environment

- Industry competitors: According to the trade liberalization of the ASEAN Economic Community, CLMV are interesting countries for the foreign investors. Therefore contractors from various countries have been entering the CLMV construction market. It is found that in Laos, there are a large number of foreign contractors from Japan, China, Vietnam and Thailand while in Myanmar, most of foreign contractors come from Japan, China, Singapore, Vietnam, South Korea and Thailand. To compete with other foreign contractors, Thai contractor has been accepted and satisfied by the project owner in terms of quality standard and schedule control however the construction cost is relatively high, compared to the construction project managed by contractors from other countries.
- Threats of new entrants: Owing to the specific characteristics of construction industry, particularly a large amount of capital and financial support, the new entry rate of the entry-level contractors is relatively low. Similarly, those contractors either domestic or foreign companies, who already entered the CLMV construction market, have already invested a large amount of money on the construction business and, their investment takes a longer time to be paid off, so the exit rate is also relatively low.
- Bargaining power of buyers: The buyer in this context means the project owner that in this situation may have a high bargaining power. It is important for the contractors to understand the factors of consideration of the project owners when appoint a particular contractor.
- Bargaining power of suppliers: Construction materials and equipment costs are significant aspects in construction projects. The efficiently materials and equipment cost controlling could result in, more profit to the contractors. Most of the contractors use construction materials produced from their own country.
- Threats of substitute products or services: A number of factors are necessarily taken into account when the substitute products or services would be applied. For instance, the reliability and the financial status of the substitute contractor are concerned by the project owners in order to compare the different between each contractor before selection.

2) Social environment

- Politics and law: To operating construction project in CLMV countries, Thai contractors need to study the domestic laws, regulations and construction work procedures. The regulations and guidelines of each country may be varied times by times and sometimes they are subject to the government officers who implemented them.
- Economic: Economic conditions of the CLMV countries i.e. Laos and Myanmar has been positioned in the growth stage. Increasing number of infrastructure and building projects provide opportunities for Thai contractors to compete in these markets. The local governments of the CLMV countries may consider to ease some

regulations or restrictions in order to motivate the overseas business sector and attract more foreign investing in the countries.

- Society and culture: Most of CLMV countries are Buddhism nations so, they are likely to share the similar values. However, it is necessary for the investors to learn about the local society and culture of each country. The contractors in the planning and management of the construction project, cannot ignore these matters.
- Technology: As the interview with related parties, it is found that the development of construction technology in Laos and Myanmar is still inefficient. Therefore, they need to import technology, equipment, tools and machinery including raw materials and construction materials such as cement and steel bar from other countries, especially from Thailand.

<u>Internal factors</u>

1) Company organizational management

- Financial management: Traditionally, the Thai contractor, who enter to construct work in foreign countries such as Laos or Myanmar, needs an initial capital for various stages in the project management processes. As a result, a large amount of investment capital is needed for managing the construction project.
- Construction project management technique: After bidding process and contract signing, the contractors will review the construction plan before the construction begins. Considering the construction technique, this study found that construction techniques are not the problems for Thai contractors. The construction quality of Thai contractors has achieved the construction standards which was accepted by the project owners in the CLMV countries. Customers are very satisfied with the quality of Thai contractors' work.

2) Human resources potential

- Motivation : Thai contractors who run the construction project in the CLMV countries mostly employ Thai workforce. The employment of Thai workforce in order to work in the foreign countries should consider reasonable motivation for the workers, mostly in term of compensation. In addition, a challenging work in the assigned project is seen as one of an incentive for new generations' workforce.
- Personnel characteristics: Thai contractors mostly arrange the construction project management team such as engineers, architects and technician from Thailand while the unskilled labor depends on each project. Sometimes they uses Thai labors but some projects they hired the local labors.

5.3. SWOT Analysis of Thai contractors in the construction project management in the CLMV countries

In managing construction projects, Thai contractors in the CLMV countries should begins with the analysis of the internal environment (strengths and weaknesses) and external environment (opportunities and threats) as shown in Table 1.

Table 1. SWOT analysis of Thai contractors in construction project management in the CLMV countries

Strengths (S)	Weaknesses (W)
S1. Thai contractors are recognized for qualified construction work.	W1. The operation cost of Thai contractors is relatively high.
S2. Thai contractors have sufficient capability to work in the international market especially in ASEAN countries.	W2. The construction materials cost is relatively high, due to the additional operation cost and risk management cost.
S3. Thai contractors use construction materials as identified in construction drawings and specifications.	W3. The labor cost of Thai contractor is higher than local contractors or contractors in some countries.
S4. The construction materials produced from Thailand are accepted as qualified products.	W4. Lack of funding and financial support.
S5. Thai contractors adopt the advanced construction technology which was accepted by most project owners.	W5. Lack of language skills especially English, local language.

Table 1. (continued)

Strengths (S)	Weaknesses (W)
S6. Thai contractors have more experience in a variety of construction types than the local contractors.	W6. Lack of communication skills and working command.
S7. Thai contractors have high operating standards and systematic construction management.	W7. Lack of the motivation for Thai workforce to work in the CLMV countries.
S8. Some of large scale Thai contractors have a chance to build a networking with local parties in CLMV countries to create a partnerships.	W8. The opportunity of SME contractors to get a job is difficult. If there is no network relationship with the local project owner.
Opportunities (O)	**Threats (T)**
O1. The economic development policy of the CLMV countries create the demand of construction projects by both public and private sectors	T1. International transportation systems are not convenient and not qualified as international standards.
O2. The establishment of AEC creates more opportunities in both construction projects and construction materials markets.	T2. Local laws and regulations has been frequently changed.
O3. International financial support, assistance and international trade privileges for developing countries.	T3. The process of requesting permission from government agencies is complicated and unclear.
O4. Joint venture with foreign countries especially ASEAN countries will strengthen the capability of Thai contractors.	T4. The process of construction building permission have various contact organization.
O5. Development of industrial zones and Special Economic Zones (SEZs) to support foreign investment.	T5. The banking system is still not standardized and procedures are quite complicated.
O6. Creating of other industrial developments related to the construction industry such as material production, logistics.	T6. Limitation of basic infrastructure systems. Many transportation networks are under developed.
O7. Proximity to the boundary checkpoints.	T7. Lack of skilled labor.
O8. Abundant natural resources in the CLMV countries.	T8. Obstacles from natural climate to construction work.

5.4. Competitive Strategy of Thai contractors in the construction project management in the CLMV countries

Based on the analysis of strengths, weaknesses, opportunities and threats of Thai contractors in the CLMV countries which using TOWS matrix concept, 4 competitive strategies are established, namely aggressive strategy (SO Strategy), corrective strategy (WO Strategy), defensive strategy (ST Strategy) and proactive strategy (WT Strategy).

Table 2. Competitive strategies of Thai contractors in the construction project management in the CLMV countries

SO Strategy		ST Strategy	
S1O1	Selection of specific construction projects based on working experience	S5T5	Bidding for the project with the project owner who have reliable background and financial credibility.
S2O2	Management of construction project by employing workforce in technical level and skilled workers from Thailand while hiring unskilled workers from local area.	S5T7	Implementation of standardised innovation and working system to develop the standard of local workers
S3O7	Using of construction materials from Thailand, by purchasing and delivering with the logistics system through the checkpoints of the border where is the nearest to construction site.	S6T7	Selection of projects that Thai contractors have competitive technology support while local contractors lack of experience.
S7O6	Adjustment of the procurement system for materials and equipment by transferring the responsibility of purchasing materials to the project owners	S8T3	Forming investment alliances, including the project owner, investor, distributor,
WO Strategy		**WT Strategy**	
W3O6	Operating subcontract work with specialization skills, such as building mechanical and electrical systems	W3T7	Cost reduction by hiring local workers or foreign workers in that country
W8O4	Building network and relationships with investors of each country in order to promote the organization	W7T7	Creating incentives other than increasing remuneration for professional personnel

Table 2. (continued)

WO Strategy		WT Strategy	
W5O2	Development of language skills for better communication	W8T4	Local partnership to create an alliance and network for investment before entering the market
W6O2	Development of management skills for improving productivity	W1T1	Curriculum development for improving construction skills in construction sites in foreign countries

Normally, formulating competitive strategies depend on the situation of the organization in each period. By analyzing the internal and external environment of construction project management in the CLMV countries, it is able to determine the competitive strategies of Thai contractors which can be discussed as a strategy for managing construction projects in CLMV countries as follows;

Competitive strategies consists of cost leadership strategy, differentiation strategy and focus or niche strategy. [6] For the use of the cost leadership strategy would be difficult for Thai contractors because the results from this study found that in the CLMV countries, Thai contractors have higher construction costs than domestic contractors, because of labor costs and construction material costs, operating fees, as well as the provision of various risks. In addition, there are competitors in the construction market in the CLMV countries, which are contractors from China with low construction costs. According to Wang, Y. & Zuo, J. [7], it is concluded that China's international construction companies use low-cost labor and labor-intensive and take the advantages from low cost of construction materials, especially those which are produced in China.

From the analysis of this study, it was found that Thai contractors are outstanding in the quality of work, using standard quality of construction materials, with high technology and have working experience in large projects. Therefore differentiation strategy should be applied in managing construction projects in this CLMV countries, as follows;

- Managing specific construction project based on direct working experience.
- Operating construction project that have specialized technologies.
- Building relationships with customers by providing quality construction project management services.
- Branding strategies for better awareness and royalty.

Since the construction sector consists of various kinds of work, such as construction work, sub-contracting, building system, consulting work, construction project manager, procurement of material and equipment, logistics system, etc. Focus or niche strategy should be applied in order to reach target customers directly, as follows;

- Working as subcontractor in specific areas such as building systems, or particular work that requires specific techniques that local contractors do have enough competency.
- Recruiting technical level workforce and skilled labors from Thailand while hiring the unskilled labor from local areas.
- Transferring the responsibility of material procurement to the project owner.
- Operating logistics system for construction materials and equipment.

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Conformance Evaluation of Lean Integrated Project Delivery (LIPD) For Indian Construction Industry

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Abstract

Integrated project delivery (IPD) can be used to improve project outcomes using a collaborative approach through early involvement of parties and a multiparty agreement. Lean construction refers to the application & adaptation of the Toyota Production System (TPS) concepts and principles in construction projects for the reduction of waste. Over the last 20 years, the construction industry has become less efficient despite having good project delivery systems like Integrated Project Delivery (IPD), Design-Build (DB), Design-Bid-Build (DBB) and Construction Management Risk (CMR). The amount of waste (man, money, material & time) in different construction activities needs to be minimized to the maximum possible extent. An efficient project delivery system is missing for the Indian construction projects. This research work introduces Lean Integrated Project Delivery (LIPD) as a solution which uses a combination of lean management principles & IPD for waste reduction during construction activities. Further, LIPD conformance would be carried out in the Indian construction industry for the successful implementation of new project delivery system by identifying Critical Success Factors (CSF). Till date, there is no research carried showing LIPD conformance in India. Data for this research has been collected using questionnaire survey using Saaty's scale from experts working in several construction industries of India and has been analyzed using Analytical Hierarchy Process (AHP). The sample size for research work is 40, which was collected from 24 different construction & project management companies in India. This paper elaborates conformance of LIPD in India and the reason for poor implementation of the same.

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Keywords: AHP; IPD; Lean Construction; LIPD; Waste Reduction;

1. Introduction

The construction industry is a challenging industry consisting of a large number of activities for completion of the project. An efficient project delivery method is required for project completion within the stipulated time and budget with minimum wastage of resources. Different project delivery systems with different characteristics have been discussed in this paper. From the period of the 1940s to 1990s Design-Bid-Build (DBB) and Construction management

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& Risk (CMR) were the most widely used project delivery methods in the United States. As the building construction has become more complex, the construction industry has become more specialized, segregating a process that was formerly directed from one master builder but still some problems are occurring with these project deliveries. So, in 1990s Design-Build (DB) project delivery was introduced as a solution [1]. This project delivery method seeks to improve project outcome through a collaborative approach, but a collaboration of all parties/teams are not done from the initial level. Some parties like contractors are included in the project after 20% completion of design [2]. So, some difficulties still remain unresolved in this project delivery method. Later, IPD (Integrated Project Delivery) was introduced to provide solutions to previously faced problems. In this method, all parties are included from the beginning of the project. However, IPD does not actively focus on reducing the waste generated during the several construction activities. According to [3], the construction industry has long been censure for being wasteful, unsafe, fragmented, inefficient, and ineffective [4]. So, a new project delivery method is required which focus on reducing construction waste along with achieving other conventional goals on any project delivery method. LIPD (Lean Integrated Project Delivery) is the perfect solution for the current challenge of project delivery systems.

Lean Integrated Project Delivery (LIPD) is a “multi-party contract that specifies the use of lean management practices as conceived in the lean project delivery system”. In other words, LIPD means “The efficiency of lean with the collaboration of integrated project delivery”. This contrast is needed because IPD only refers to the multi-party agreement, regardless of what practices are used.

2. Literature review

IPD (Integrated Project Delivery)

According to [5] Integrated project delivery (IPD), is a collaborative alliance of project participants into a process that tacks the Talents and perception of all participants to optimize project results, increase value to the owner, reduce waste, and maximize efficiency through all phases of design, fabrication, and Construction. Specifically, according to [6] IPD consists of a multidisciplinary team of design and construction professionals assembled to complete a project, who are bound together initially by alternative forms of agreement that require team members to share risk and reward, contribute equally, and employ alternative processes and technologies, all in support of achieving reduced cost, time, loss and waste metrics. (El Asmar et al., 2013) has delineated in their research after performing several compression matrices for cost, time, delay, errors and concluded that IPD performs very well with respect to traditional project delivery methods in waste generation, delay and cost overrun.

LEAN Construction & Management

As a term, lean production & management is the collective synonym for the production system that was first developed in the car-manufacturing environment at the Toyota Motor Corporation which is famous as the Toyota production system (TPS) [4] and it consists of 14 principles that can be divided in to 4P’s [7]. Koskela is the one who has lots of research on Lean and is known as the father of lean construction. Lean is a production management-based approach to project delivery which highlights on changing the traditional project delivery and work to minimize waste and to achieve maximum value. Lean focus on the reduction of the non-value added activities to decrease the amount of waste [9]. According to [10] Inspired by Koskela’s (1992) important study of production theories in construction, industry has embraced lean principles for nearly one and a half decade. Most research and implementation has focused on construction processes, especially addressing the waste inducing effects of poor planning Some work has extended to the design process, and even lean project delivery although, the results have not yet matched those achieved by Toyota manufacturing. Lean Construction is considering several tools like LPS (Last Planner System), Visible Management, Just in time(JIT) Technology, Total Quality Management(TQM), 5S &6S on-site Management ,huddle meetings, first run studies [9] & [11] which are mainly focusing on the reducing amount on waste in construction activity in terms of man, money, material, and time.

3. Methodology

Primarily, this research focuses on identifying Critical success factors (CSF) associated with the implementation of Lean Integrated Project Delivery (LIPD) in India and the objective of this study is to investigate CSF factors of LIPD in detail and more systematically through identifying construction industry perspective towards combined project delivery in India. This research project collected its data using the questionnaire survey method. The specific methodology was based on a literature review, Face-to-Face interview, and a questionnaire survey. The research steps are as follows,

- ***Factor identification:*** Through literature survey of past 15-20 years and semi-structural interviews with field experts having 15 years plus experience, total 78 different critical success factors were identified for successful implementation of a LIPD in infrastructure projects in India.
- ***Formation of questionnaires:*** The questionnaire was designed according to Satty's *scale (1-3-5-7-9)* [12], like **1**=Two criteria contribute equally to the objective, **3**=Experience and judgement slightly favour one over another, **5**=Experience and judgment strongly favour one over another,**7**=Criterion is strongly favoured, and its dominance is demonstrated in practice, **9**=Importance of one over another affirmed on the highest possible order & **2,4,6,8**=Used to represent compromise between the priorities listed above. The entire questionnaire is divided into 5 parts, ***1)*** General introduction of the respondent, ***2)*** Factors related to IPD, ***3)*** Factors Related to waste generation, ***4)*** Factor related to Lean Management, ***5)*** Factor related to conformance.
- ***Data Collection:*** respondents were given the option of answering the questionnaire in Google docs online that included in E-mail or completing it in hard copy. And based on this data has been collected. The questionnaires were filled by the differ field persons like Project Manager, Contractor, Site Engineer, Planning engineer, site supervisor, PM Consultant, Designer, developers etc.
- ***Data analysis and Discussion:*** All the collected data is stored in excel sheets. For the interpretation of data collected, we use the Analytical Hierarchy Process (AHP).

4. Data collection & analysis

Data Collection

Major data collection is done with the help of a questionnaire survey. A total of 74 numbers of questionnaires were distributed to respondents ranging from Project Manager, Contractor, Site Engineer, Planning engineer, site supervisor, PM Consultant, Designer, developers having 5-15 year of construction industry experience involved with different project delivery methods. Selection of the respondent was done by stratified random sampling. The reason for using stratified random sampling is that it can represent each preference group proportionately. On the other side, the construction companies were chosen from the top 50 companies that have a wide range of experience in handling big projects.
To ensure better responses, the surveys forms were distributed by hand and follow-up were made via telephone. Such efforts ensured better response and help to explain its objective while obtaining broader inputs from the respondents. Still, out of all questioners, we get only **40** responses back which includes, Project Manager (8), Contractor (5), Site Engineer (7), Planning engineer (6), site supervisor (5), PM Consultant (7), Designer (3). So, by this, we can consider that awareness & seriousness towards research work in the construction field is very less.

Data Analysis

For the data analysis, we choose the Analytical Hierarchy Process (AHP) for differentiating the most critical success factors using the hierarchy process. So, here is some process for calculation. The first step is to prepare the pair-wise comparison matrix as shown in ***eq.-1*** using the values which are obtained in data collection**.** The 2nd matrix of pairwise comparisons A = [a_{ij}] represents the intensities of the expert's preference between [13]

individual pairs of alternatives (Ai versus Aj, for all i,j=1,2,..,n) according to [12] is derived from values of matrix-1 as shown in ***eq.-2***. Our main goal is to compute a vector of weights $\{w_1,w_2,...,w_n\}$ associated with an eigenvector method, w is the weight vector.

$$W=(Wi/Wj)=\begin{bmatrix} W1/W1 & W1/W2 & \cdots & W1/Wn \\ W2/W1 & W2/W2 & \cdots & W2/Wn \\ \vdots & \vdots & \ddots & \vdots \\ WnW1 & WnW2 & \cdots & WnWn \end{bmatrix} \ldots. Eq \rightarrow 1 \qquad A=(aij)=\begin{bmatrix} 1 & a12 & \cdots & a1j \\ 1/a12 & 1 & \cdots & a2j \\ \vdots & \vdots & \ddots & \vdots \\ 1/a1j & 1/a2j & \cdots & ain \end{bmatrix} \ldots. Eq \rightarrow 2$$

In the **3rd step,** each matrix is normalized and be found the relative weights. The right eigenvector gives the relative weights (W) corresponding the relative eigenvalue λ-max), as ***Eq.-3.***

$$Aw = \lambda\text{-}max * w \ldots\ldots\ldots. Eq.\text{-}3$$

After that Priority of eigenvalue (PV of EV) is calculated.

In the **4th step,** the consistency is calculated. it is defined by the relation between the entries of [14] A: a_{ij} x a_{jk} = a_{ik}. The Consistency Index (CI) can be calculated, using the following ***Eq.-4.*** Where n=number of responses.

$$CI = \frac{\lambda max - n}{n-1} \quad \ldots\ldots\ldots\ldots \textbf{\textit{Eq.-4}}$$

Using the final consistency ratio (CR) can conclude whether the evaluations are sufficiently consistent. The CR is calculated as the ratio of the CI and the random index (RI), as indicated in ***Eq.-5.***

$$CR = \frac{CI}{RI} \ldots\ldots\ldots\ldots \textbf{\textit{Eq.-5}}$$

The CR value ≤ 0.12 then it is accepted upper limit for CR [14]. In bellow table N= numbers of factors.

Table 1: (RI Value tables for calculation)

n	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
RI	0.88	1.10	1.24	1.34	1.40	1.44	1.48	1.51	1.53	1.55	1.57	1.58	1.59	1.60	1.61

5. Result and discussion

After analysis of all the collected data using AHP, we can get the following results which are shown in ***Table: 2 to 8***. The table also shows the weighted distribution of the factors according to the PV of EV values. The top 16 Critical factors were according to Values (PV of EV) and arranging the brainstorming session with respected field experts. The CR value is ≤ 0.12 for all 7 tables. Which means the values are according to the accepted upper limit for CR [14] So, we can consider matrix as a consistent one & calculations are satisfactory.

Table-2: Factors which are responsible for successful completion of the project on schedule with design cost

Factors	PV-of-EV	Rank
Trust on team members during the project	**0.072**	**1**
Project delivery/implementation speed	**0.072**	**2**
Communication between team members	**0.071**	**3**
Continuous improvement in work performance project by project	0.071	4
System quality throughout the project	0.070	5
Conflict resolution between teammates	0.069	6
Construction speed	0.068	7
Working in different teams	0.066	8
No blame Culture	0.066	9
lost time injuries	0.065	10
Amount of design change during the project	0.064	11
Gain and pain sharing of work in the project	0.063	12
The requirement of extra labor then schedule	0.062	13
amount of re-work in the project	0.061	14
Waste recycling rate	0.061	15

Table-3: Factor responsible for Delay in Planning

Factors	PV-of-EV	Rank
issue related to funding and another monetary parameter	**0.143**	**1**
lack of knowledge for one of kind project	**0.143**	**2**
Frequently change in requirement from the client	0.133	3
the issue in land acquisition	0.132	4
Environmental clearance	0.120	5
inappropriate attitude from the client	0.113	6
Site Clearance	0.108	7
Objection from a nearby organization	0.108	8

from the ***Table-2*** we have selected top 3 factors having maximum values for PV of EV from 0.071 to 0.071 and ***Table-3*** we have selected top 2 factors having maximum values for PV of EV from 0.133 to 0.143 as a critical factor.

Table-4: Factors responsible for waste caused in the Construction industry (Management Stage)

Factors	PV-of-EV	Rank
Frequently design change	**0.060**	**1**
Poor design coordination among project participants	**0.060**	**2**
Slow decision making	**0.059**	**3**
Waiting for equipment	0.059	4
Poorly scheduled delivery of material to the site	0.059	5
Lack of control	0.058	6
Poor planning	0.057	7
Waiting for skilled labor	0.057	8
Poor layout of the site	0.055	9
Poor Site management	0.055	10
Over Allocation of material	0.054	11
lack of worker training	0.054	12
Lack of trust	0.053	13
Too few supervisor and foreman	0.053	14
Over Allocation of equipment	0.052	15
Over Allocation of workers	0.052	16
Waiting for material	0.051	17
lack of design information	0.051	18

from the ***Table-4 & Table-5,*** we have also selected top **3** factors having maximum values for PV of EV from 0.059 to 0.060 and 0.082 to 0.084 as a critical factor.

Table-5: Factors responsible for waste caused by "Human Resource/ labors)" in project

Factors	PV-of-EV	Rank
The understanding between engineers and labors	**0.084**	**1**
Lack of supervision causing relief in workers	**0.084**	**2**
Unnecessary labor movement	**0.083**	**3**
Rework and repair required due to defective work	0.081	4
Waiting for labor	0.081	5
Mishandling or error was done by labor	0.079	6
Theft of material / Equipment	0.076	7
Accidents	0.074	8
Unnecessary leave	0.073	9
lack of proper knowledge of work	0.072	10
Unnecessary resting	0.072	11
The health of the workers	0.070	12
Unnecessary chaos	0.070	13

Table-6: Factors responsible for waste caused by "Equipment" in project

Factors	PV-of-EV	Rank
Waiting for equipment	**0.138**	**1**
Error in erection of equipment	**0.133**	**2**
Use of outdated equipment with problematic parts	0.132	3
Unnecessary movement and transportation within the site	0.125	4
Mishandling or error caused during the work	0.120	5
Time is taken for maintenance	0.119	6
Miscommunication between the driver and signalman	0.117	7
Driver having less knowledge	0.115	8

from the ***Table-6*** we have also selected top 2 factors having maximum values for PV of EV from 0.133 to 0.138 as a critical factor.

Table-7: Delay in the supply of material

Factors	PV-of-EV	Rank
Late information	**0.211**	**1**
The inappropriate attitude of supplier	**0.207**	**2**
Higher demand for material in the market	0.200	3
Transportation	0.193	4
Very less required product	0.189	5

from the ***Table-7*** we have selected top 2 factors having maximum values for PV of EV from 0.207 to 0.211 as a critical factor.

Table-8: Causes of degradation of the material

Factors	PV-of-EV	Rank
Lack of proper storage space	**0.184**	**1**
Poor handling	0.183	2
Maintenance of storage area not done	0.164	3
Quality check is not done	0.158	4
Negligence by caretaker	0.157	5

And from the ***Table-8*** we have selected factor having maximum values for PV of EV is 0.184 as a critical factor. Another major thing which is noticed during data analysis regarding the LEAN Construction and IPD knowledge in the people of construction industries in India. Which is shown in ***fig.-1*** as a spider web diagram and abbreviation of Figure are in ***Table-9.*** On the basis of that, we can say that awareness is very less in people. Only 35% of people know LEAN, IPD and Work with this Project delivery.

Table 9: Abbreviations for Fig: 1

A1	**Know** ***IPD*** concept and **Work** with this concept.
A2	**Know** ***IPD*** concept but **Not Work** with this concept.
A3	**Don't Know** ***IPD*** concept and **Not Work** with this concept.
A4	**Know** ***LEAN*** concept and **Work** with this concept.
A5	**Know** ***LEAN*** concept but **Not Work** with this concept.
A6	**Don't Know** ***LEAN*** concept and **Not Work** with this concept.

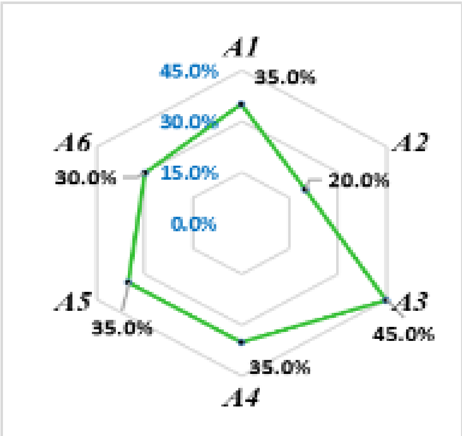

Figure 1 : (Spider Web Diagram for awareness & work experience in LEAN & IPD)

From the ***figure-1*** we can say that the awareness regarding the LEAN and IPD in the construction industry of India is very less.

6. Conclusion

This paper proposes an evaluation of Lean Integrated Project Delivery (LIPD) conformance among the construction industry of India. The use of LEAN Construction & IPD by the Indian construction industry is still in its infancy. Although some professionals have worked on either IPD or LEAN or both projects, a majority either does not have direct experience or not familiar with this concept. So, to work with a combination of these concepts is quite difficult. Although according to factors derived from the AHP analysis we can say that Lean Integrated Project Delivery (LIPD) has its conformance among the construction industry of India but the implementation of this requires around 10-15 years. For that, the education of LEAN & IPD in construction studies is required from the earlier stage of engineering studies. These are some of the reason which delays the implementation of LIPD in India. These factors are 1) less awareness regarding the research work in construction, 2) a huge amount of competition in the market, 3) no time to learn new technology, 4) lack of knowledge & skills in labours and 5) lack of training & resist to the change.

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Construction experts' perceptions on the influence of emotional intelligence on leadership development.

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Abstract

Notwithstanding the significance of leadership within organisations and social settings, there seems to be less information about the influence of emotional intelligence on leadership development in the construction industry. The purpose of the research was to establish the influence of emotional intelligence on leadership and leadership development in the construction industry. The ongoing leadership challenge in the construction industry seeks research to determine the importance of emotional intelligence in leading teams. The research launched with an extensive review of literature in order to identify the core and sub-variables which embodies emotional intelligence and leadership for leadership development. A three iterative round Delphi technique was conducted to attain consensus of the identified emotional intelligence indicators. A list of experts was generated from peer-reviewed conference proceedings and industry executives. The rating of the influence was rated between low influence and very high influence. Data collected were analysed using Microsoft Excel, a spreadsheet software. The results indicated that emotional intelligence is essential and those that seek to think critically should show a different characteristics of emotional intelligence. The study contributes to the literature and empirical research underpinning on emotional intelligence in the construction industry.

Keywords:Construction industry; Emotional Intelligence; Construction Industry

1. Introduction

Leadership is defined as the ability to continually deliver superior performance to the benefit of oneself and the organisation. Likewise, given the current construction business context, Charlton [1] deems emotional competencies vital for organisational success. Research on emotional intelligence (EI) in the outlook of leadership has remained a recurring area of interest for more than ten years [2]. Further research has been done concerning leaders' emotional expression in the workplace and the way leadership styles impact on the emotional welfare of employees while developing organisational commitment, proactive behaviour and job performance [3].

Leadership has always been difficult in the changing times, and in the face of such occurrences people look for organisational leaders with integrity, character and can provide direction. Moreover, people who are unable to maintain a degree of control over their emotional life and fight inner battles might have a challenge in providing direction to the

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followers [4]. Nevertheless, ongoing debate continues regarding the contribution of EI to our understanding of leadership [5]. Thus, this study focuses on evaluating the influence of emotional intelligence and its sub-variables on leadership development.

2. Leadership

In the midst of many authors Bass [6] defines leadership as an intentional influence by one person over others. Antonakis [5] defines it as a process of organisational influence intertwined with different relationships. Much of the existing leadership studies places emphasis that leadership is the ability to adapt to different situations. Much more to the construction industry, project leaders amount for everything that happens within a project, making it vital for them to understand leadership and its constructs. Moreover, if one word were to define construction management, it would be responsibility. Skipper [7], stated that a leader should always guide followers towards organisational goals. Numerous others have characterized leadership as far as practices, qualities, skills and results of leaders. Stephen Covey has his seven habits for successful people and eight attributes of focused leaders [8]. Bass further distinguishes leadership as a learnable arrangement of practices [9]. These various and uncertain meanings of leadership suggest that leadership can appear to be unique in various circumstances. No one definition is right or superior to the next. Leadership is influenced by various factors and can be seen from a wide range of points of view.

Furthermore, it is important to note that the context of leadership in this article is in the construction industry, and we can define leadership in this setting, as leaders and managers in charge of a construction sites' progress and its success. Project leaders are responsible for all that happens in a project. Moreover, it is also evident that the industry has a greater urgency for leadership than arguably any other industry. Many reasons support this notion, and it is evident by looking at the construction projects, and the constructed products [10].

3. Emotional Intelligence

There has been numerous definitions of Emotional Intelligence (EI) [11] [12] and they all share a similar theoretical foundation, which comprises of awareness of one's own emotions; and awareness of emotions in others; and understanding of emotions and the ability to manage all emotions. The two noticeable models of emotional intelligence incorporate an ability-based model [13] and a skill-based model [14], which differ in their conceptual method toward the application of EI. The ability-based model centres on EI according to intelligence theory, emphasising the cognitive fundamentals of EI and using a performance-based assessment method known as the Mayer- Salovey-Caruso Intelligence Test (MSCEIT). The skills-based model is trait-based and encompasses a broader set of competencies [14]. In this framework, Bar-On [11] defines EI as being a cross-section of interrelated emotional and social competencies, skills, factors and facilitators that determine how effectively we understand and express ourselves, understand others and relate with them and cope with their daily demands [15].

Emotional intelligence discourses the emotional, personal, social and survival extents of intelligence, which are vital for daily cognitive practices. EI elaborates an understanding of self and others. Goleman's dimensions of emotional intelligence include;

Self-awareness: The ability to be aware of which emotions, moods, including impulses one is experiencing, and why. This dimension is also indicative of an individual's awareness of the effects his or her feelings have on others.

Self-regulation: The ability to maintain one's own emotions and impulses and to remain calm and composed in volatile situations, irrespective of one's emotions.

Motivation: The ability to remain focused on goals, despite setbacks. This dimension also indicates an individual who can operate from hope for success rather than a fear of failure.

Empathy: A person's ability to understand the feelings conveyed through verbal and non-verbal messages and providing emotional support when needed.

Social skills: The ability of individuals to handle problems without demeaning others who work with them'. This dimension ‘also includes the ability to refrain from letting one's negative feelings towards another individual inhibit collaboration, and to handle conflict with tact and diplomacy.

4. Methodology

The methodology section gives a detail of methodology used to determine the influence of emotional intelligence for leadership development. A Delphi survey was conducted among 14 experts (academics and built environment professionals and business owners) in South Africa. A Delphi study is a group decision mechanism requiring qualified experts who have a deep understanding of the issues at hand [16]. Each expert was required to meet some of the following criteria:

Knowledge: Knows construction management and project management; knowledgeable in leadership research, knowledgeable in the field of management theory. Academic Qualification: Has an earned degree (National Diploma/B-Degree/M-degree/PhD) related to any field. Post-doctoral, training, certification employment and experience focusing on sustainable development issues, psychology, construction management, project management and social sciences. Experience: Has a history or currently is performing consultation and contracting services within the construction industry, individuals, businesses, agencies, companies, and organisations, related to construction and infrastructure context. The experts must exhibit a high degree of knowledge of experience in the subject matter and an extensive theoretical knowledge thereof. Research: Has submitted one or more proposals to or has received research funding (grant/contract) from national, provincial, local government, regional, and private sources that support housing development and studies for the low-income group or other human settlement-related issues. Membership: Be a member of a professional body. Should be the representative of a professional body so that their opinions may be adaptable or transferable to the population. Finally, Willingness: Panel members must be willing to participate in the entire Delphi study fully.

The recommendations of Rowe et al. [17] were adopted for the current study, whereby they stated that the number of respondents should be large enough to ensure that all perspectives are represented, but not so large as to analyse the results unmanageable by the researcher [18]. Five of these criteria items were considered than the customarily recommended two. Experts were required to be in managerial positions and also have an understanding of leadership development. The initial Delphi survey was made up of 20 experts comprising academics and construction professionals who were randomly selected based on the criteria. The experts applied their knowledge on the concept raised in the study, based on the criteria developed in the questionnaire. From the 20 experts invited to participate in the Delphi survey, 14 responded and completed all the three rounds. This number of experts was considered adequate based on the literature recommendations from scholars who have previously employed the technique. [18] suggested that since most studies incorporate between 8 and 16 experts, eight experts are reasonable. Experts were asked to rate the impact factors influencing emotional intelligence for leadership development in the construction industry as shown in table 1. Data obtained from the survey were analysed with Microsoft Excel spreadsheet software. The output from the analysis was a set of descriptive statistics.

5. Findings

Findings from the Delphi survey shows the (13) listed emotional intelligence measurement variables, that were identified by the experts as influencing leadership development. When assessed, findings revealed 12 measurement variables to have reached consensus with IQD cut off (IQD ≤ 1) score (See table 1). 8 variables managed to reach the median score of 7, which implied a very high impact (HI: 7-8.99). One variable managed to reach a median score of 9 which implied a very high impact (VHI: 9-10).

Table 1. Emotional Intelligence Attributes

Table 1: Emotional Intelligence Attributes	Median	Mean	SD	IQD
Ability to think critically	**9**	9,14	0,36	0,00
Emotional resilience skills	**8**	7,71	0,83	0,00
Ability to manage distressing emotions	**8**	7,93	0,27	0,00
Ability to manage personal fears	**8**	7,79	0,58	0,00
Ability to know what motivates your employees	**8**	7,93	0,62	0,00

Self-management features	**7**	7,14	0,53	0,00
Social awareness features	**7**	7,07	0,47	0,00
Relationship management features	**7**	7,07	0,83	0,00
Social judgement skills	**7**	7,00	0,68	0,00
Ability to understand feelings of team members	**7**	6,93	0,62	0,00
Ability to listen to moods and emotions of team members	**7**	7,00	0,68	0,00
Ability to distinguish amongst feelings of team members	**7**	7,00	0,68	0,00
Self-awareness features	**6**	6,57	0,76	1,00

SD = Standard deviation; IQD = Interquartile deviation

Results from the survey revealed that the following 13 emotional intelligence measurement variables were considered by the experts to have varying impact on leadership development in the construction industry.

- Self-awareness features (MI)
- Self-management features (HI)
- Social awareness features (HI)
- Relationship management features (HI)
- Social judgement skills (HI)
- Emotional resilience skills (HI)
- Ability to understand feelings of team members (HI)
- Ability to listen to moods and emotions of team members (HI)
- Ability to distinguish amongst feelings of team members (HI)
- Ability to manage distressing emotions (HI)
- Ability to manage personal fears (HI)
- Ability to know what motivates your employees (HI)
- Ability to think critically (VHI)

From the impact ratings of the factors; findings revealed that 12 of the factors had high impact, while only one had a very high impact.

6. Discussion of findings

This section presents the discussions of the findings from the Delphi survey on the impact of emotional intelligence variables on leadership development in the construction industry. Findings revealed greater influence in the ability to think critically as vital and this corresponds with the findings by [1]. Further findings revealed the need for social awareness features which concurs with findings by [10,11,12]. This however calls the need for leadership training in this regard.

7. Conclusion and Recommendations

The purpose of the study was to determine the impact of emotional intelligence on leadership development in the construction industry. Findings revealed that the ability to think critically as a leader is of importance to leadership development. It is recommended that institutions should start introducing leadership education and training programs that can help instil the critical elements of emotional intelligence in the construction industry.

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Critical Traits for Effective Leadership Style in the South African Construction Industry

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Abstract

Leadership is associated with certain traits or set behaviours that characterised the leader and which to some extent is essential for influencing others for maximum cooperation and productivity. In some cases, actions may speak better than words. People follow a leader not only because of what he/she says, but what he/she does or is made of. In other words certain qualities are responsible for effective leadership. However, researchers are still oblivious of which trait would always guarantee leadership success. Hence, the search for better leadership traits has continued to this day. Leaders may find themselves in demanding circumstances characterised with complexity, pressure, and uncertainties such as construction and its industry. In such situation, certain leadership traits may be critical more than others for a leader to make headway, as well as influence his/her subordinates towards salvaging the situation to a great extent. The main objective of this paper is to investigate the critical traits for effective leadership among construction professionals in the South African construction industry. The primary research data were collected through a structure questionnaire while the secondary data were collected from a detailed literature review. The survey was conducted in the Gauteng Province of South Africa. Respondents were construction professionals especially project managers. Respondents were selected using heterogeneity and convenience sampling techniques. Data from the questionnaire were analyzed using Statistical Package for the Social Sciences (SPSS) version 23.0 software. Values were represented with descriptive statistics (mean) and standard deviation and were ranked according in descending order. Findings from the study revealed that ability to communicate well is of the optimum importance for effective leadership. Other findings include organised, integrity, self-discipline, experience, courage, visioning, empathy, honesty, problem solving ability, passion, creative, self-confidence, flexible/open to change, ability to inspire/motivate, composure, decisiveness, action oriented, risk taking, foresight, teachable and charisma. The study contributes to the body of knowledge on the effects of effective leadership for optimum performance in the South African construction industry.

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Keywords: Construction industry; leadership, leadership traits.

1. Introduction

Leadership studies have been approached in many different ways and views. In some cases, it is define as a process of guiding, directing and commanding others to achieve a desired goal as [7, 11]. In other words, it is a process by which a person influences others to accomplish an objective and directs the organization in a way that makes it more cohesive and coherent [3]. It is vital to understand that leadership is neither a position nor management. Leadership is that extra edge to management [17, 25]. The goals of managers come from "necessities" but the goals of leaders come from a

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place of "active attitudes" [25]. As leadership is an extra plus for management, so also an active attitude to Leadership [17, 24]. A manager can quit when the goings are down but a leader carries the burden upon him. A leader goes the extra mile and as well make the followers go also [17]. Maxwell [17] further posit that real leaders have the courage to face their fears, challenge the way things are, risk everything for the cause they believe in and do all that with no regard to personal gain [17]. This means that attitude, traits and qualities are major characteristics of leadership [10]. Hence, a leader's behavior, traits and attributes can be used consistently to influence the subordinates in the attainment of the desired goal [5]. Good Leadership ability is therefore critical for any construction organization to implementing a high performing culture of productivity and effective improvement [6]. The ability of the project leaders and superintendents to effectively motivate and navigate their subordinates will determine the success of the labour on the job [9]. In addition, the fact that the construction industry is characterized with complex and changing situations makes good leadership traits and abilities essential for overcoming challenges as well as the attainment of the project deliverables [20]. To this effect, this paper investigates the predominant leadership traits of construction professionals in the South Africa construction industry.

2. Leadership traits and attributes

Leadership traits can be defined as personal qualities and attributes that shape effective leaders [8]. These qualities and attributes can be inherent or learned [2, 4]. The influence an effective leader has on the subordinates is a product of firm balance of traits, attributes and behavioural pattern used in leading them [5, 15]. Hence, the trait theory focused on the analysis of mental, physical and social characteristic to gain more insight on the common characteristics among leaders [24]. The predominant thought was that the identification of traits calls for accurate prediction of a leadership ability in an individual or potential leader in the making [2, 24]. There are many qualities that make an effective leader of which there appears to be no guaranteed consensus [13, 15]. People behaviours, cultures and circumstances differ. Therefore, in any giving situation the effectiveness of the leader inter-alia will depend on the exhibition of the right qualities and traits [13]. An effective leader's personality traits should be seen not only within the boundaries of work but also outside its boundaries. This helps the leader achieve success and satisfaction in both work and personal life [5]. This is true with the popular saying that a leader can become the one he or she ought to be on the outside by first fixing his/her self on the inside. The acquisition of adequate leadership traits among construction professionals and as project leaders is essential to pushing team members toward performance enhancement in any project undertaking.

2.1. *Personality traits of effective leaders*

Literature has suggested a plethora of traits which can characterise effective leaders [1, 17, 20, 21]. Maxwell [17] in his 21 Indispensable qualities of a leader listed such traits like:"Integrity, charisma, commitment, communication, competence, courage, Discernment, Focus, Generosity, Initiative, Listening, Passion, Positive attitude, Problem solving, Relationships, Responsibility, Security, Self-discipline, Servanthood, Teachability, and Vision". Kirkpatrick and Locke [14] suggested that the elements of leadership trait are drive; desire to lead; honesty and integrity; self-confidence; and knowledge of the business. Other researchers like Ogunlana [20] as well as Barker and Coy's [1] also suggested traits like, desire to lead, Integrity, Humility, courage, humour, passion, compassion, wisdom, self-confidence and knowledge of the business. Furthermore, literature has revealed some perceived traits of leadership inter-alia which can thrive well particularly from the construction industry perspective of which include, inspiration, motivation and rewards consciousness [15, 21]. To this end, some of the prevalent leadership traits of effective leaders are expounded below.

- Communication skill

The leader should be able to get a message properly across to followers. Effective communication helps group members to follow through with the given instructions. The key to effective communication is simplicity. The ability of a project leader to listen, understand what others mean, and verbally persuade people effectively is attribute of good communication skill [13].

- Organised

The hallmark of effective leader is the ability to be structured and well organised. In other word, planning skill is vital for effective leaders. A leader who does not plan for himself and for the organisational activities is only planning to fail. Ability to plan includes judgment, perceptual foresight, conceptual foresight, ordering, elaboration and adaptive flexibility [15].

- Integrity

According to Maxwell [17] foundation of true leadership is "character (integrity)" as people will not willingly follow the leader to whom they distrust. Integrity is also very essential in moral leadership. It can bring a lasting success. An effective leader should do what he/she talks about always as a good example to his/her subordinates. Leaders must not only be honest and trustworthy but also trust their group members or followers

- Visioning

Vision is everything for a leader because it fuels the fire within which helps draw the leader and the subordinates forward. Jarad [13] defines visioning as a process which is categorised in phases such as the creation stage, improvement stage as well as the renewal stage of the vision. Many researchers assert that the goals of visioning include giving insight on the future to the organisation, guiding the decision making and connecting to the values [22].

- Self-confidence

The quality to believe in oneself is also pivotal if one is to accomplish anything here on earth. Without self-confidence, it is hard for a leader to take the bold step of convincing his/her subordinates or team that the challenging goal is possible to be attained [21].

- Flexible

Flexibility is vital today considering the advances in technology, global outsourcing and employees' attrition challenges etc. Therefore, the possession of flexibility is required if he/she is to cope with the changing environments and downsizings in the society [5].

- Courage

One of the most vital qualities useful for any undertaking is that of courage. This trait is essential because it helps the leader to face the day to day challenges that life may bring and the risk that goals with the attainment of each goal [5]. In addition, leadership starts from within (the heart of a leader) where courage resides [23]. Furthermore, it will be difficult to display other skills such as integrity, communication skill, decisiveness, inter-alia without courage [23].

- Empathy

The ability to understand another person's feelings, experiences etc. is one of the effective traits a leader can possess. A leader should be able to see things from others point of view. Being sensitive to others, understanding their feeling and finding the best way to communicate with them should be a priority for any leader [16].

- Passion and Motivation

Leaders with high energy and enthusiasm towards their goal never quit. This is because they are being fuelled by the above-mentioned forces which enable them to press on despite difficulties they may encounter in the way [16, 17]. Effective leaders use various forms of motivation where necessary in effectively moving the group forward.

- Commitment

Commitment is what separate doers from dreamers. A leader should be able to persist in what he believes and get amidst obstacles. A leader is constantly under a watchful eye by the subordinates. Any slip in commitment will clearly be seen by the subordinates. Hence, it is important to maintain an attitude of commitment to the organisational objectives, as well as to the team.

- Teachable

A leader should always be teachable. To keep leading the leader should keep learning. It is a popular saying that "all leaders are readers". As a leader, your growth determines who you are and who you are will either affect your organisation positively or negatively [17].

- Composure

Maintaining a good composure and stability are not only good for in leadership but also play a good role in managerial efficiency [15]. Stable leaders are intelligent about their emotions. The understanding of one's own strength and weakness and the seeking of improvement where necessary are factors that make for an effective leader.

- Problem solving

Problem-solving skill is essential for any leader. With problem-solving ability, the leader can analyse adverse conditions or conflict, differentiate between causes and symptoms [13]. As per Maxwell [17], Leaders with Good issues taking care of capacities suspect issues, acknowledge reality, can see the comprehensive view, handle one thing at once, and never abandon a noteworthy objective when they are down.

3. Research methodology

A quantitative approach was adopted for this study. Hence, a questionnaire was used as a tool for the collection of the primary data. Quantitative research is one of the practical approaches to gather information from an extensive sample of respondents using statistics [18]. It involves a survey to obtain information from a sample of people by means of self-report whereby a sequence of questions are posed to the respondents by the researcher [12].The questionnaire was constructed using a 5-point Likert-scale survey. Weights were assigned to each response ranging from 1 to 5 from "strongly disagree" to "strongly agree". A convenient sampling was used, targeted at 81 construction professionals in the Gauteng Province of South Africa. 63% response rate was achieved. The professionals were limited to project managers, architects, quantity surveyors, construction managers, civil engineers and town planners. Data were analysed using the Statistical Package for Social Sciences (SPSS) version 23.0 software. The reliability and internal consistency of the collected data were appraised using Cronbach's alpha α. α value for the leadership style actions was 0.76. Mean (M)) value was used and the various leadership traits were ranked accordingly.

4. Findings and discussions

The empirical findings centred on the critical traits for effective leadership in the South African construction industry. Results according to table 1 revealed that good communication skill is very essential for effectiveness when leading people. Hence, it ranked first with Mean (M) value of 4.50 and having standard deviation (SD) value of 0.74. It was also revealed that effective leaders are much organised (M=4.26, SD=0.92). Integrity was ranked third (M=4.24, SD=0.94) while Self-discipline and commitment were ranked fourth position having the same value (M=4.22, SD=0.93). Other vital traits mentioned were as follows: Experience (M=4.18, SD=0.94, R=6); Courage (M=4.12, SD=0.82, R=7); Empathy (M= 4.06, SD=0.91, R=8); Visioning (M=4.06, SD=0.92, R=9); Problem solving ability (M=4.02, SD=0.84, R=10); Honesty (M=4.02, SD=0.84, R=10); Passion (M=4.00, SD=0.93, R=12); Creative (M=3.96, SD=1.00, R=13); Self-confidence (M=3.92, SD=0.90, R=14); Open to change (M=3.82, SD=0.94, R=15); Ability to inspire/motivate (M=3.82, SD=0.92, R=16); Composure (M=3.80, SD=0.67, R=17) etc. However, *Teachable* and *Foresight* have the 2nd and 3rd lowest mark having the mean value of 3.66 (SD=0.77, R=21) and 3.54 (SD=0.73, R=22) respectively. Finally *Charisma* was ranked last (R=23) with Mean value of 3.48 with SD=0.76.

Table 1: Critical Leadership traits

Dominant Traits	Mean	Standard Deviation	Rank
Communication skill	4.50	0.74	1
Organised	4.26	0.92	2
Integrity	4.26	0.94	3
Self-discipline	4.22	0.93	4
Commitment	4.22	0.93	4
Experience	4.18	0.94	6
Courage	4.12	0.82	7
Empathy	4.06	0.91	8
Visioning	4.06	0.92	9
Problem solving ability	4.02	0.84	10
Honesty	4.02	0.84	10
Passion	4.00	0.93	12
Creative	3.96	1.00	13
Self-confidence	3.92	0.90	14
Flexible/Open to change	3.82	0.94	15
Ability to inspire/motivate	3.82	0.92	16
Composure	3.80	0.67	17
Decisiveness	3.76	0.66	18
Action oriented	3.74	0.85	19
Risk taking	3.70	0.81	20
Foresight	3.66	0.77	21
Teachable	3.54	0.73	22
Charisma	3.48	0.76	23

5. Conclusions

The study set out to establish the critical traits essential for leadership effectiveness in the South African construction industry. The essence of leadership and its traits was clearly discussed. Findings revealed that good communication skill when dealing with people is very critical for effectiveness. In addition, it was also revealed that self discipline of a leader and commitment are very essential for influencing people. This is because, before one is qualified to lead others, he/she should first a lead himself/herself. Additionally, a leader is always on the spotlight and any slip in commitment will clearly be seen. Hence, a slack in commitment can affect the commitment of the subordinates. It can also reduce the quality of influence the leader has on the subordinate. Finding also revealed that a leader should possess certain traits like experience, courage, empathy, visioning and problem solving ability. People tend to listen to the leader who is a master in his/her craft. In addition, no one would like to follow a wimp as a leader and a person who does not know where he or she is going. Furthermore, people will listen to the leader who is able to understand their own feelings and able to sort out situation with the best possible option. Other important findings include creativity, passion, good composure, decisiveness, action-oriented, risk taking, foresight, a teachable attitude and charisma. This study provides useful insight on key traits which when characterised a leader will enhance the influence he/she has on the subordinates. In addition, these traits when possessed or developed in abundance can help the leader to press the right leadership style buttons as occasion demands. Pressing the right leadership style button will then influence the subordinates and cause them to achieve the desired objectives. Project objectives when then achieved result to organisational success and in turn contribute to business growth of the industry and gross development product of the South African nation.

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Current Supply Chain Management in Construction Industry

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Abstract

Supply Chain Management (SCM) in construction industry is a developing field of study. This paper analyses the results of a questionnaire survey on supply chain management in top US construction industries. A survey was sent out via online tool to more than 100 contracting companies in the US, mapping the relationship between contractors and suppliers, the tools and methods employed in executing the supply chain practices. The survey results indicated that SCM in the construction industry is still in its developing state. They also indicated that the construction industry has been relatively slow in adopting SCM as a tactic due to its complexity and uniqueness. The study recommends several solutions to overcome the above mentioned problems and improve the efficiency of the SCM in the construction industry.

Keywords: Construction Industry, Supply chain, Construction Supply Chain Management, ANOVA ;

1. Introduction

The construction industry is a major contributor to the Gross Domestic Product (GDP) of many countries. In the United States, the construction sector employs more than 6 million people and accounts for about $3.4 billion to GDP. As many scholars' states construction sector as a back bone to the economic development of a country. With advances in technology and management aspects throughout the entire world, these strides do not lead to the implementation of supply chain management principles.

Supply chain principle adoption in various industries has led to successful results. SCM comprises of logistics, sourcing, and transporting raw materials, to deliver end products to customers [1]. The advantages of implementing these principles are numerous such as enhanced communication and information sharing between contractor and suppliers, customer satisfaction, cost reduction, and responsiveness. The important factor pressing against the implementation of these principles is the fragmentation of the construction industry [2]. There is a lack of communication between the participants, namely, clients, contractors, subcontractors, and suppliers, which leads to disputes and delays.

In order to address the demands of the construction industry, this paper analyses the current status of supply chain management in the construction industry [3]. A survey was conducted to shed some lights on the relationships between contractors and suppliers, tools and methods used in implementing supply chain practices, and the principal objectives in developing SCM. The survey results help understand the construction industry stand on supply chain principles.

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2. Survey result

A five-page survey was sent to a wide range of construction companies in the United States. For the analysis, the respondent companies were classified into three groups, namely, small, medium, and large. The classification, which was based on the workforce and annual turnover of their companies.

The survey has been divided into five sections to investigate supply chain relationships. It starts with the demographic information of the respondent's company. Then, the survey asks for the factors that reduce the efficiency of supply chain management practices. Next, the survey inquiries about the conflict causes between contractors and suppliers as well as supply chain tools and methods. Finally, the questionnaire addresses risk mitigation methods in case of emergencies and the flexibility performance incorporated in the supply chain.

The survey was designed with the important factor as to define and analyse the scope of responsibilities in the construction industry [4]. With the understanding of literature reviews, the issues pressed against supply chain principles were derived. To have a detailed understanding of the collected results and to make a qualitative analysis, it is common to have ordered categorical data, where responses to statements may be rated as Very Low, Low, Moderate, High, and Very High or Strongly agree, Agree, Neither Agree nor Disagree, Disagree, Strongly Disagree. With ordered categorical data the number labels should form a rational sequence, because they have some numerical meaning, namely, 5, 4, 3, 2 and 1.

The survey was sent out to 100 contractors in the United States using the online survey tool 'Survey Monkey'. A total of 67 responses were received. The reply percentages from small, medium, and large companies were 29%, 24%, and 47%, respectively. Table 1 summarizes survey reply results.

Table 1: List of activities

Companies in Groups	Responses	Percentage
Small Workforce (i.e., less than 5,000 workers)	19	28.8%
Medium Workforce (i.e., between 5,000 and 10,000 workers)	16	24.2%
Large Workforce (i.e., larger than greater than 10,000 workers)	31	47.0%
Small Workforce (i.e., less than 5,000 workers)	19	28.8%
Total	66	

The percentage of respondents from commercial, industrial, and residential construction companies were equal to 46.27%, 34.33% and 19.40%, respectively. Table 2 summarizes the response results by construction industry type.

Table 2: Response results by construction type

Specialization in Construction	Responses	Percentage
Industrial	23	34.33%
Residential	13	19.40%
Commercial	31	46.27%
Total	67	

3. Factors impacting SCM efficiency

The first set of questions asked the contractors about the factors reducing the efficiency of supply chain management. To enhance the performance of supply chain, the common problems associated between contractors and suppliers were derived. The literature review indicated five critical factors. The results, which are summarized in Table 3, show that the most important problem is the lack of command flow in supply chain. The involvement of many sub-contractors and suppliers leads to delays and complexities that increase disputes between supply chain members. The extended time buffers between each supply chain process and poor communication between your company and suppliers are also potential problems. Even with the advancements in technology, there is a lack of information sharing and communication in the construction industry. With the use of database and computer algorithms, the participants can be interconnected and monitored. Apart from these, isolated geographical locations and placing the material order without proper design data are considered to have less impact on supply chain management efficiency.

Table 3: Survey response for factors reducing the efficiency of SCM

Function	Very Low	Low	Moderate	High	Very High	Total
Poor Communications between your company and its suppliers	11	16	12	15	6	60
Extended(long)"time buffers" between each supply chain process	0	1	22	23	14	60
Lack of Command flow in the supply chain	0	1	21	24	14	60
Isolated geographical locations in supply chain	7	22	19	11	1	60

4. Causes of problems between contractors and suppliers

The survey results, which are summarized in Table 4, show that lack of planning is considered as the most important causes of problems between contractors and suppliers are the lack of control by supplier and insufficient communication.

Table 4: Problem causes between contractors and suppliers

	Responses			
Function	Small	Medium	Large	Total
Poor Communications between your company and its suppliers	11	16	12	15
Extended(long)"time buffers" between each supply chain process	0	1	22	23
Lack of Command flow in the supply chain	0	1	21	24
Isolated geographical locations in supply chain	7	22	19	11

5. Tools and methods of supply chain

5.1. Mapping of critical functions

Mapping of critical function in the supply chain starts at its basic level, by monitoring all the persons participating in the process at every single stage. It consists of our suppliers and their networks in obtaining raw materials to delivering to the end customers. The most underrated basic technique of SCM is mapping and drawing of our critical functions. With the growth of our company network, the supply chain becomes twisted network.

5.2. Client-Supplier diagram

Both client and supplier should have a proper understanding of their scope. With the better relationship it increases performance and boosts rapid delivery of quality of products to the end destination [5]. Close relationship between client and supplier is maintained when there are less suppliers involved [6] and it becomes more complex with large complex project. Mapping of critical functions can assist the client supplier differences to overcome.

5.3. Productivity measurement

Productivity measurements are used to measure and enhance the efficiency and the quality of the business services. Traditional measurements are considered to be ineffective, as they do not separate non-value-added costs [7]. Additionally, supplier's evaluation and client satisfaction survey were regarded as positive feedback if used with proper knowledge.

5.4. Waste identification survey

Waste identification survey was considered as one of the most underrated technique in supply chain management [8]. This technique was considered as a significant method to reduce cost and time. With the proper mapping of raw materials to end products, wastes can be minimized.

Table 5: Tools and methods used in supply chain

	Responses						
	Yes			No			Total
Function	Small	Medium	Large	Small	Medium	Large	
Mapping of Critical Functions	15	12	30	2	0	0	59
Client-Supplier Diagram	9	10	6	5	2	24	56
Productivity Measurement	12	11	19	5	1	8	56
Cause-effect Diagram	9	6	13	7	8	14	57
Brainstorming	8	7	15	9	4	13	56
Effective Meeting Techniques	13	11	29	3	0	1	57
Documentation System	15	10	27	2	2	0	56
Client Satisfaction Survey	8	7	7	9	5	20	56
Waste Identification Survey	6	6	5	10	6	22	55
Suppliers Evaluation	11	9	16	5	3	12	56

The results of the survey on tools and methods are summarized in Table 4. The contractors were asked to select the significant tool to improve the efficiency of SCM. The most effective tool selected by the respondents was mapping of critical function, followed by effective meeting techniques and productivity measurement. The least effective tools were waste identification and client satisfaction surveys. Moreover, waste identification client satisfaction surveys were regarded as positive feedback if used with proper knowledge.

With the advancements in technologies, the tools employed in SCM are subjected to continuous growth. Using GIS applications to monitor logistics and RFID tags [9] to monitor material availability on construction sites are advancing methods used in the construction industry supply chain. The fragmentation in the construction industry can be overcome by connecting all the participants and updating the information on the database pool.

6. Principal objectives in developing supply chain management

The last section of the survey was about the principal objectives in developing supply chain management in the construction industry. Implementing the supply chain principle can bring various benefits to the company with that objective in mind, few factors were selected for this section and contractors were asked about their opinion on these principals. The survey results, which are summarized in Table 6, show that the benefits to the client's was the main objective in developing SCM, followed by increased market competitiveness and increased profitability. An ideal company should work on benefiting client by reducing the costs within the company, which can aid in market competitiveness and increased profitability. By following these principles, products are delivered on time, which benefits the clients. This scenario is a win-win situation for all project participants.

Table 6: Principal objectives in developing supply chain management

Function	Small	Medium	Large	Total
Benefits to the clients	15	13	30	58
Increased profitability	16	12	17	45
Increased market Competitiveness	14	15	17	46
Benefits to the Suppliers	9	8	8	25
Cost Reductions Within the company	4	2	1	7
Improved quality assurance	4	1	1	6

7. CONCLUSIONS

In order to gain competitive advantage over others, supply chain management and partnership, which evolved from Japanese car manufacturer, are used in many other industries. Although the supply chain made its way into every industry, the construction industry has been relatively slow to adopt SCM due to its uniqueness of the product, the change in locality of the project and several other characteristics that was almost irreplaceable at the beginning. Because of their significant role in the construction industry, the contractors were surveyed about their opinions of different areas of supply chain management.

The study reveals that the contractors are more favored towards benefitting the clients rather than giving equal importance to the suppliers. Instead of forming a contractual agreement with its suppliers for the many years to come, they certify them based on different parameters and provide incentives to appreciate their success. Most of the small companies tend to avoid forming a contract as it is set a bind them together for years. Also, the communication in the supply chain seems to be a main concern affecting the performance. Thus, focusing on improving the efficiency by creating a compatible communication system within the supply chain can prove significant.

The survey also revealed that the suppliers lacked the planning of the process and then controlling it after. Planning by the contractor alone isn't sufficient enough as the supplier needs to be take control of his part of the supply chain. But this defect can be easily rectified just by conducting training sessions by the supplier. Competent workforce minimizes the chance of error and also reduces the time involved between each link in the supply chain on the supplier's side. The lack of involvement and support by the top management also affects the supply chain.

Among other problems, the US construction industry needs to implement the above mentioned tools and techniques by laying certain rules and regulations. They should also set their principal objectives clear of benefitting both their clients and suppliers in addition to cutting their costs.

Implementing SCM to the fullest scale benefits in various ways such as reducing waste linked to the supply chain, cutting down costs, increasing market competitiveness and profitability in addition to other indirect ones. Even-though supply chain management is catching on in the US construction industry, there are some of the factors that need to be looked upon in order to achieve high performance and increase its efficiency.

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Developing A Lessons Learned Database for NCDOT Projects Using Design for Six Sigma (DFSS) Approach

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Abstract

Valuable lessons and best practices learned from construction projects often fail to get transferred to future generations due to the lack of a formalized process. This perpetual problem gives rise to the need of imparting fresh training to new inductees once the aging workforce retires or in the event of turnover in an organization. This paper aims to facilitate the process of disseminating knowledge gained in the transportation area by developing a lessons learned database named Communicate Lessons, Exchange Advice, Record (CLEAR) under the auspices of the North Carolina Department of Transportation (NCDOT). A Six Sigma approach to Identify, Define, Develop, Optimize, and Verify (IDDOV) was used to develop the CLEAR database. The IDDOV model in Design for Six Sigma (DFSS) is a five-step process in designing efficient and robust new systems. The first phase involved conducting interviews with end-users as well as reviewing existing data within NCDOT data repositories such as claims and supplemental agreements data to better understand challenges and issues in need of resolution. With this information as basis, an outline for web-based database was created from which feedback was solicited. After taking into consideration all preferences from these end-users, the web-based database was fine-tuned to reflect all comments and suggestions gathered by the research team. This database is currently being populated from ongoing pilot projects. In the final stage of this project, the CLEAR database will be launched throughout the state on all ongoing projects. These five project phases reflect the principles of the IDDOV method of Six Sigma which provides the foundation for developing this database. Findings from this study will help NCDOT to institutionalize knowledge and improve project cost variations and schedule predictability. The success metrics include anticipated reduction in number of claims, claim amounts and increased coordination among staff within NCDOT.

Keywords: Knowledge management; Lessons learned; Organization efficiency; Six Sigma; Web-based database

1. Introduction

Construction is a complex process involving methods and activities unique to a project that are seldom repeated on other projects in the same sequence. Construction companies constantly strive to improve their workflow by preparing

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robust schedules and periodically documenting project progress. Despite having sound procedures in place, companies still face issues that can lead to delays and claims, thereby causing financial loss and/or loss in reputation. One of the primary reasons for this is failing to document valuable knowledge learned by the personnel in their work. A lot of useful knowledge gained through years of experience goes waste if not documented properly and at the right time. This is especially true in organizations with high turnover or older personnel retiring from their positions, giving way to younger generations. Although the younger generations may be full of zeal in finishing tasks assigned to them, lack of access to previous experience may devoid them of the ability to make sound decisions. The concept of lessons learned systems (LLSs) has been gaining importance and are being deployed to utilize important knowledge gained over time. The greatest advantage of having a good LLS is to reduce rework and put to practice what worked well or did not work very well on a project. The Project Management Institute (PMI) defines lessons learned as the learning gained from the process of performing the project [1].

This paper describes an effort to design and implement a lessons learned database throughout North Carolina Department of Transportation (NCDOT). Additionally, NCDOT is currently facing turnover issues like any other organization and there is an urgent need to document lessons for later use. Lack of formalized processes compounds the problem and thus the lessons learned database will assist personnel to revisit past experiences rich in knowledge and bring in organizational changes to improve processes within the organization.

The proposed lessons learned database will be an internal only database that is mainly intended for personnel associated with all project phases within the construction domain in NCDOT. There are 14 divisions throughout the state. A Design for Six-Sigma (DFSS) approach for this project has been proposed which can be considered as novel in this field of research since previous research on designing lessons learned databases have overlooked this approach. A DFSS model allows for robust systems to be designed right from the inception till its design complete. This project makes use of the Identify-Design-Develop-Optimize-Verify (IDDOV) model of DFSS to design this database.

Design for Six Sigma (DFSS) methodology is a systematic and disciplined problem preventing approach which is widely used to design robust engineering systems. There are many models that utilize DFSS for generic technology development such as I^2DOV (Invent, Innovate, Develop, Optimize, Verify), CDOV (Concept, Design, Optimize, Verify), IDDOV (Identify, Define, Develop, Optimize and Verify); DMADV (Define, Measure, Analyze, Design and Verify) to name a few [2]. While the above-mentioned models have their own benefits and drawbacks, the research team utilized the concepts of the closed loop IDDOV model that starts and ends with the customers. The actual scale of implementing this IDDOV model is not the same as used in the manufacturing or related sectors but drawing inspiration from them. Fig. 1. depicts pictorially the five steps of the IDDOV model as applied to the CLEAR database creation. The research team explored various models and selected the IDDOV model most suited to design the database and to build an error-free robust lessons learned database. Beyond a doubt, DFSS can be considered a natural fit for software development process (SDP) owing to similar approaches [3].

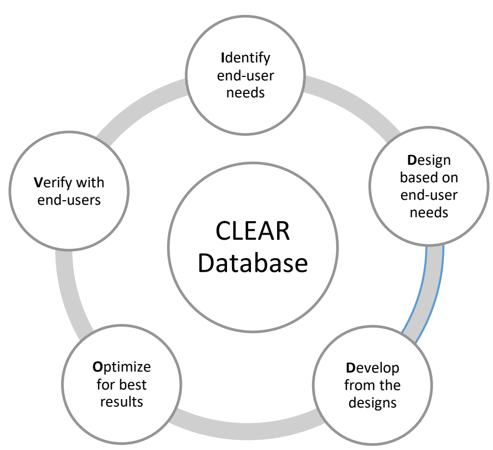


Fig. 1. Six-Sigma DFSS Approach Using IDDOV Applied to CLEAR Database

The Design for Six Sigma (DFSS) is a part of Six Sigma philosophy that is applied while designing novel systems. Sokovic and Pavletic [4] provide the following definition for DFSS:

"DFSS methodology is a systematic and disciplined approach to product or process design, including all organizational functions from the early beginning, with the objective to design things right from the first time".

Six Sigma concepts can be applied at any phase in a project, depending on its need and the final requirements. The Define, Measure, Analyse, Improve, and Control (DMAIC) model is the most popular model within Six Sigma [4] [5]. As can be seen from Fig. 2., the DMAIC approach is best suited to improve existing processes. In contrast, the IDDOV model of DFSS is best suited for novel design requirements. Since the NCDOT lessons learned database is being created from the outset, the IDDOV model served in the best interests of the research team. The five phases of IDDOV as applied to this project are described in section 2.2.

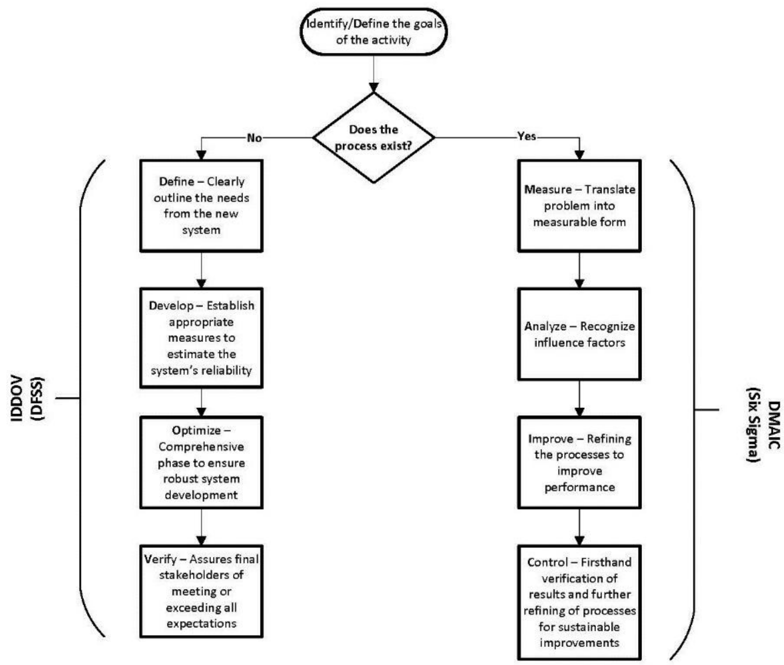


Fig. 2. Typical decision approach for traditional Six Sigma (DMAIC) and DFSS (IDDOV)

1.1. Background

Currently, there is no formal mechanism in place within NCDOT for sharing useful knowledge among design, construction, and maintenance personnel and within the fourteen divisions throughout the state. There is a silo-type mentality and hence very limited communication on project successes and failures among people exists. This gives rise to two problems. First, there is in no way to inform the other divisions/personnel about a particular method or product other than a direct contact in a conference or telephone. Owing to immense work pressures, there is little time for personnel to convey successes and failures to each other. Second, the very fact that something can be done better by following certain steps remains with each person and is not effectively conveyed to others. Thus, there is a need to establish a method of collecting lessons learned to share valuable knowledge among design, construction, and maintenance staff. This information will help improve design guidelines, best practices, revise specifications and bring to light innovations that have taken place on projects that could be used throughout the NCDOT organization. Effectively sharing information of this nature can reduce project costs and improve project delivery.

This project involves the collection and dissemination of both lessons learned and best practices during the preconstruction phase, execution phase (considering detailed design and construction), and maintenance and operations—essentially covering all aspects of the project lifecycle. A user-friendly, web-based accessible database in SharePoint will be used to both collect and communicate lessons learned and best practices. The database would be sortable by major trends for the various groups within NCDOT.

1.2. Previous Work

Organizations have now realized that there is a need to store and retrieve useful lessons. Previous research on this topic has explored various approaches for lessons learned experiences in the construction industry [6]. Additionally, the Kentucky Transportation Cabinet funded a study to develop a constructability lessons learned tool used during the design phase to improve project outcomes [7]. Fong and Yip [8] measured the level of readiness of construction professionals in Hong Kong about being open to implement lessons learned systems within their organizations. They utilized a survey instrument to solicit information from construction professionals to learn about the current practices of recording and retrieving lessons learned in organizations within Hong Kong and to understand the critical design aspects for a lessons learned system from an end-users perspective. One of their research finding was that construction personnel did not prefer to record lessons while the project was ongoing, which can lead to important knowledge being lost. This is one of the pitfalls the current research has taken note of and aims to avoid.

Lessons learned exercises have been an integral part of improving processes in an organization. It has been recognized as one of the 17 best practices identified by the Construction Industry Institute (CII) for achieving enhanced project performance [6]. Lessons learned act as a valuable constructability resource to planning and design teams to help identify potential problems in advance and thus be proactive in mitigating possible schedule and cost overrun issues.

The Construction Industry Institute (CII) report on lessons learned [9] acts as an invaluable resource in the field of knowledge management. This report highlights the three main phases of a lessons learned exercise as collection, analysis, and implementation. Establishing the right culture and upper management support is also essential to establishing a successful lessons learned program. The authors also suggest that in an organizational structure, knowing what to document and where could impact the effectiveness of a designed lessons learned tool. Most organizations have now started to realize the full potential of a lessons learned program within their organizations. For instance, NASA has both a public lessons learned system (PLLS) as well as internal lessons learned information system (LLIS). The U.S. Army Construction Engineering Research Laboratories (CERL) uses DrChecks, which utilizes client-server architecture for comment sharing among various parties pertaining to design documents over the web.

The Indiana Department of Transportation (INDOT) was an early adopter using a lessons learned database. In consultation with researchers McCullouch and Patty [10] at Purdue University, a series of interviews was conducted with personnel at INDOT to improve coordination between the design and construction teams aiming to achieve a better constructability review program. A windows-based constructability lessons learned software application was developed using visual basic. Folio Views is the software that contains the Constructability Lessons in text form and is also used to store, index and retrieve the lessons.

A similar research activity was performed jointly by Kentucky Transportation Center and University of Kentucky. Goodrum et al. [11] surveyed resident engineers, contractors, and consultants to obtain an initial understanding of what they envisioned to be a perfect lessons learned database. The team came up with relevant data fields to be populated in a web-based lessons learned database which could accept files both in text as well as image format. Each user associated with the database was classified into three categories – end user, gatekeeper, and administrator with each of their functions clearly stated. The database was structured into two parts – one for users to enter new lessons learned and the other for storing and retrieval of cleaned up lessons. MS Access was implemented for data storage and retrieval while MS FrontPage was used to accept lessons learned input from users. The database also had provision to search for specific terms within the database fields to yield specific results helpful for design teams during a constructability review. The MS Access database however had a capacity of just 2000 rows and the plan was to link this database with an Oracle database for wider reach [11]. However, this effort did not seem to be very successful as the lessons learned database ran a high risk of being defunct once the 2000 rows limit was reached in case of failed integration.

2. Research Methodology

2.1. Overview of Six Sigma Philosophy

The term Six Sigma was coined by engineers working in Motorola during the ‘80s and has since been adopted by other major corporations such as Toshiba, General Electric, Ford Motor Company. The six-sigma philosophy is a statistics-based concept that is widely used in multiple business sectors these days. It focuses on better understanding of end-user requirements, improving business systems throughout the organization by reducing the amount of errors and continuous improvement of all organizational business systems. The ultimate benefits of adopting six-sigma model are improved quality and delivery of products, development of robust processes, and sustained competitive advantage [5].

Six Sigma philosophy aims at minimizing the number of defects and reducing variation in processes. The Greek letter Sigma signifies the standard deviation for a population. In the context of Six Sigma, this standard deviation is directly proportional to the process variation. That is, the Sigma value reduces with reduction in process variation and vice versa. Mathematically, Six Sigma aims at achieving 3.4 defects per million opportunities (dpmo) which is near perfection, whereas a three Sigma process aims at achieving about 66,807 dpmo [12]. Over the years, there have been many versions of Six Sigma that were conceptualized by organizations based on their requirements. The Define, Measure, Analyze, Improve, and Control (DMAIC) is widely considered as one of the most popular Six Sigma data-driven quality strategy to improve processes and for quality control in an organization. Thus, it becomes important to distinguish between Six Sigma and Design for Six Sigma (DFSS). While Six Sigma process improvement is a method for improving process performance and capability without process redesign, DFSS is a Six Sigma strategy that focuses on the early stages of a product/process life cycle [13]. Table 1 below shows the differences between Six Sigma and DFSS as applied to a business model for various associated business elements required by an organization. At this point, it is reiterated that this project utilizes the beliefs of the DFSS model but does not employ any associated statistical measures and/or related calculations. The five phases of IDDOV as applied to the CLEAR database is as described below.

Table 1. Differences between Six Sigma and DFSS [14]

Element	Six Sigma	DFSS
Focus	Existing process	New process
Goal	Reduce variation	Reduce variation and optimize performance
Action taken	Analyze	Design
Best suited for	Maximizing current process	Developing new products
Major effect is on	C_P (reducing variation)	C_{Pk} (centering within customer requirements)

2.2. IDDOV Model of the Database

2.2.1. Identifying needs and understanding trends

This is the first step in the process and includes the necessary steps to be taken to form an initial structure of the database and to collect information about end-user’s database requirements. The research team prepared an interview guide containing a list of questions asking the respondents about their preferences for a lessons learned database and to understand the current trends within NCDOT. The current trends imply the existing practices of recording data pertaining to claims, supplemental agreements, and other useful relevant data at NCDOT. The contact details of each potential respondent/end-user was provided by the NCDOT Value Management office. Since this process involved human interaction, an Institutional Review Board (IRB) approval was required from the appropriate university authority prior to acquiring information. An interview request was sent by email to 66 potential respondents at the

NCDOT. By the end of this phase, 32 interviews were conducted with 46 personnel with a total of 813 years of work experience. Most of these interviews were conducted over the telephone, but a few were performed in-person.

2.2.2. Defining the Database

After the research team was able to gather information on the trends and end-user requirements for the database, a qualitative analysis was performed to come up with the necessary database fields. It was important to not miss out on any relevant information and hence there were at least two sets of entries for each interview in Microsoft Excel sheets. At the end of the interviews, both the Excel sheets would be carefully investigated to ensure that all data had been captured and documented properly. The initial design of the database had three segments. The first segment captured basic respondent information. The second segment captured details about the lesson or the best practice with a provision to attach relevant files and images to augment information. The final segment included details regarding the project such as project number, contract number, project type, claims and supplemental agreement information.

2.2.3. Developing the Database

The third phase of the project involved developing the lessons learned database using the designs arrived at using the information gathering phase from end-users. Since this is an internal-only database and developmental information is accessible to NCDOT users alone, the Information Technology department within NCDOT (NCDIT) was tasked with developing the web-based database on a SharePoint portal using Microsoft Access. This combination was chosen because NCDOT currently has an active SharePoint portal for its normal operations and hence a preferred option by the end-users. The research team is currently working towards obtaining lessons learned files from the respondents. At this time, 29 lessons learned files were collected from 15 personnel contacted in the first phase. These files were submitted to the NCDIT to be populated in the newly developed pilot database. Additional respondents are being contacted to solicit more lessons learned. Once all the lessons are entered into the pilot database, the research team plans to visit a few pilot projects currently being constructed to check for the possibility of collecting more lessons from site engineers, inspectors, resident engineers, and other site personnel.

2.2.4. Optimizing the Database

The CLEAR database is being created to cater to all the 14 divisions of NCDOT and has a few functionalities that draw upon information from other central databases such as HiCAMS, a repository for NCDOT contract data. During the data gathering phase, the team identified that NCDOT personnel did not want to spend more than 5 minutes entering a lesson or searching for relevant ones. Hence, it became imperative to streamline information such that accurate information can be entered/accessed in a timely fashion. Additionally, since large amounts of space in the form of images and files and attachments can be expected for each lesson entered, careful attention needs to be given to allocate adequate space in the database. Thus, the need to optimize the database periodically based on the development in the previous stage. The KyDOT lessons learned database was initially designed for 2000 entries and thus had a huge risk of running out of space [11]. During a formal conversation with one of the engineers that worked with the Kentucky Transportation Center revealed that their database ran out of space within a year or so of its deployment once all the 2000 rows got filled. This fact was noted by this research team to avoid repeating the same mistake.

2.2.5. Verify for completeness

After all the previous steps have been performed, the database will be reviewed and tested by end-users to provide feedback regarding their satisfaction of the new lessons learned database. These comments will be collected and given to the IT team at NCDOT for possible improvements. In short, the team will verify the completeness of the system and rectify any shortcomings. All the five steps will be then repeated in an order till the gatekeeper finalizes the wholeness of the database as can be seen from figure 1. The gatekeeper would be responsible for ensuring the completeness of submitted lessons and for final uploading of these lessons into the lessons learned database. The Value Management team at NCDOT will act as the gatekeeper.

3. Results and Future Work

Currently, the research team is in the process of collecting lessons to populate the database. To date, the research team has been able to gather and handover to NCDIT 29 lessons to be entered into the pilot database. Appendix A shows a template for the lessons solicited from the end-users. The database fields were arrived at based on the initial information gathering phase. The database requirements from the end-users are as summarized below:

3.1. Database requirements

3.1.1. User friendly

- Less typing – The respondents looked forward to having more of drop-down menus to select their answers rather than typing it, as it would save some time and effort. This was however challenging for the research team but strived to bring all possible options as a drop-down menu.
- Keep data entry simple and less time consuming – Most of the respondents also mentioned that owing to multiple tasks throughout the day, it would not be possible for them to spend more than five minutes on entering/retrieving lessons.
- Avoid double data entry – Currently, work related details are entered in the engineer diaries as well as HiCAMS – a central repository to store information related to contract administration, claims, supplemental agreements. Thus, it was important to devise a strategy so that respondents did not need to enter data multiple times.

3.1.2. Easily searchable

- Display relevant and specific results – So as to not put off the respondents, it was crucial that the search results displayed were most relevant and suited to the requirements based on the search criteria. There is a risk of non-usage of the database if appropriate search lessons are not displayed which the user is searching for.
- Use appropriate filters/tags – To obtain accurate search results, users have an option to narrow down search results based on pre-defined criteria such as date observed, keywords, project type. The more information the user inputs as search condition, the better the search results will be.

3.1.3. Other desired features

- Upload images/pdf/email files – As they say a picture speaks a thousand words. Being able to upload an image file or other relevant attachments will provide better understanding of the issue and the solution taken to resolve the issue.
- Provide an impact rating (based on cost and time) – Provision to have impact ratings based on the project cost and schedule bearing direct influence on the lesson being entered. A Likert scale was mooted for rating both cost and schedule variations. This rating will be critical to search for highly meaningful impactful lessons.
- Create automatic trigger to complete a lesson learned on projects that experience claims or supplemental agreements above a certain threshold value

3.1.4. Training

- The lessons learned database can act as a training resource for fresh recruits to look up necessary lessons using the search functionality.

During the information and database requirements gathering stage, one of the key issues facing most NDCOT projects pertained to utility relocations/removal and coordination. As a result, the academic research team was requested to summarize all key findings from the interviews pertaining to utilities and submit this information to the Value Management Office for development of a special utility guide. This was validated through our interviews as well as data on claims on all NCDOT projects that was provided by the Value Management office. This gave rise to another research idea looking into the leading indicators of claims arising due to utilities which is currently being performed by the same research team. It is also planned to continue collecting and populating the pilot database and prepare for an organization wide rollout of the database around July 2019. To ascertain the success of the lessons learned database, the success measures would involve increased coordination among design, construction, and maintenance personnel. Additionally, there should be a decrease in the number of claims, supplemental agreements arising in construction projects, in addition to observing reduction in the amounts associated with them.

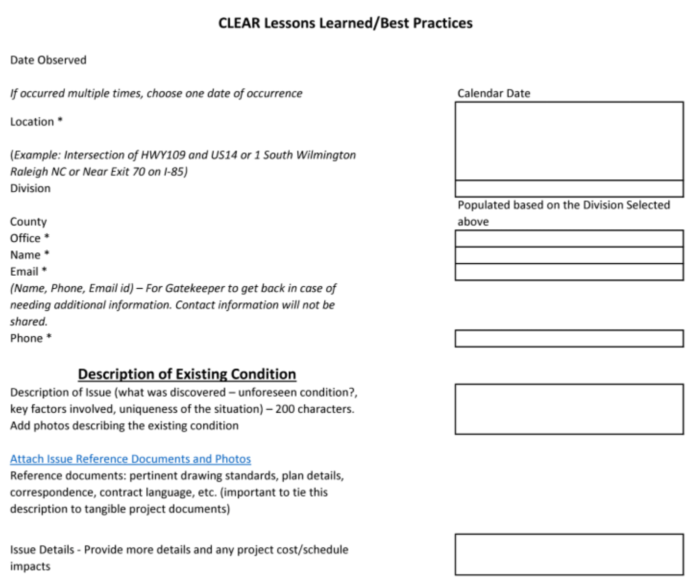
Conclusions

The lessons learned/best practices database within NCDOT would facilitate better coordination between design teams and construction teams. The overall aim of creating this database would be to achieve superior design performance and thus reduce the frequency and impact of change orders, achieve enhanced cooperation, and ultimately accomplish improved operational performance. Lessons learned are an effective way to document and retrieve wisdom gained from previous projects and to apply these learnings in future projects to attain best practices. Project teams are dynamic and seldom repeat themselves in different projects. Also, there are possibilities that the aging workforce will retire before their knowledge can be documented. In either case, there would be a significant amount of wisdom that would be lost if they are not documented in a proper lessons learned/best practice database. This will provide scope for the young generation to take cue and put into practice these lessons learned to realize desired project goals. Project teams across departments at the NCDOT will greatly benefit from utilizing this rich and robust knowledge database. In the long run, the CLEAR database will assist NCDOT to adjust future cost estimates, update standards, and change policies to continuously strive to be an effective and efficient organization to the public.

Acknowledgements

This research is supported by North Carolina Department of Transportation. We are thankful to all the NCDOT personnel who provided insight and expertise that greatly assisted the research, although they may not agree with all the interpretations/conclusions of this paper.

Appendix A. Sample Lessons Learned/Best Practices Template


CLEAR Lessons Learned/Best Practices

Date Observed

If occurred multiple times, choose one date of occurrence — Calendar Date

Location *

(*Example: Intersection of HWY109 and US14 or 1 South Wilmington Raleigh NC or Near Exit 70 on I-85)*

Division

County — Populated based on the Division Selected above

Office *

Name *

Email *

(Name, Phone, Email id) – For Gatekeeper to get back in case of needing additional information. Contact information will not be shared.

Phone *

Description of Existing Condition

Description of Issue (what was discovered – unforeseen condition?, key factors involved, uniqueness of the situation) – 200 characters. Add photos describing the existing condition

Attach Issue Reference Documents and Photos

Reference documents: pertinent drawing standards, plan details, correspondence, contract language, etc. (important to tie this description to tangible project documents)

Issue Details - Provide more details and any project cost/schedule impacts

https://doi.org/10.3311/CCC2019-039

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Design Criteria-Based Probabilistic Estimation Method for Aged Apartment Remodeling Projects in Korea

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Abstract

As apartment get older, it is required to extend the life of the buildings through remodeling and reconstruction. In this situation, members of the apartment choose one of two options. The most important thing in this choice is economical feasibility, which is greatly influenced by the construction cost. There are many cases of reconstruction projects, and accurate construction cost can be calculated. However, remodeling projects are very rare and it is difficult to calculate accurate construction cost. In addition, the remodeling is not only difficult for the members to communicate the design criteria to contractors, but also takes time to reflect them in the estimation, which also affects the decision making. Therefore, this study proposes an estimation method that can integrate the design criteria with in cost. To do this, this study analyzes design criteria based on the previous remodeling cases and classifies them to derive Design Criteria that are required by the members. And it also proposes a range of construction cost by introducing range estimation process to measure the effect of construction cost on each design criterion. In conclusion, this study has been developed an easy-to-use estimation program by combining Excel and Sketchup software. If remodeling cases accumulate in the future, the accuracy and usability of the program are expected to increase.

Keywords: Apartment Remodeling, Influence Analysis, Design criteria, Construction Cost, Estimation

1. Research Background and Purpose

In South Korea, apartments comprise the majority of residential buildings. Many apartments were built under national policies between the 1970s and 1990s. As the apartments become old and degrade as time progresses, owners wish to construct new buildings through reconstruction. Many apartments have been reconstructed accordingly. In the 2000s, however, wastage of resources became an important concern, and remodeling using the existing structures was recommended instead of reconstruction in South Korea to improve resource utilization.

However, this resulted in problems regarding the estimation of construction cost. The reconstruction cost can be obtained easily by adding the demolition cost to the new construction cost. For the remodeling cost, meanwhile, difficulties arise in the construction cost estimation from the beginning of the project. This is because no large-scale project has applied the task of reinforcing the existing structures and adding foundation to the entire complex including buildings.

Construction companies are providing rough estimations through simple information, and the reliability is low. Therefore, the willingness of companies to participate in the project is low and apartment owners cannot make a decision on the project (Lee 2010). This is because it is difficult to apply the "similar case comparison method and

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expert experience utilization method," the rough estimation methods used widely in the construction industry to apartment remodeling construction. More specifically, although apartments are typical buildings, few remodeling cases have been reported, rendering it impossible to apply the similar case method(Idrus 2011). In addition, it is difficult to apply the expert experience utilization method because construction experts who have performed the corresponding construction are few. Moreover, although construction experts would like to participate in estimation and reflect on construction cost variation factors, the risks were not classified and their effects were neither identified nor quantified (Kang 2004).

Hence, this study aims to propose an estimation method considering the design criteria required for apartment vertical extension remodeling in the beginning of the project to address the aforementioned problems. Meanwhile, BIM has been used in various areas in the construction industry recently. BIM provides visual information, rendering the communication between the owner and contractor easier. It was confirmed that this characteristic facilitates the communication of remodeling design contents. This study also utilized BIM to facilitate the communication of estimation contents between the owner and contractor in the estimation stage.

2. Research Scope and Methodology

Apartment remodeling can be classified into "small-scale remodeling" in which the indoor interior is changed, "medium-scale remodeling" in which additional horizontal extension is performed, and "large-scale remodeling" in which additional vertical extension is included. The target of this study is large-scale remodeling. It is mainly affected household unit increase by adding floors. This type of remodeling also covers underground parking lot extension and structural rehabilitation.

Typically, types of estimations are classified by the accuracy according to the progress of the project. For the purpose this study, the rough estimation has been employed method in order to properly estimate the large scale remodeling projects.

This study attempts to propose an alternative to address the aforementioned problems after analyzing the existing practices, theories, and research through the survey of previous studies.

3. Preliminary Investigation

3.1. Order of Magnitude Estimation Method

The unit area reference and expert utilization methods are being used as the current remodeling of rough estimation methods. The area reference method calculates the construction cost input to a previous case based on the unit area, and the calculated value is adjusted after an expert assessment. As aforementioned, however, this method produces a calculated value with low accuracy. This is because the current design criteria were not reflected in the construction cost of the past case.

Hence, this study attempts to propose a method of calculating the construction cost by reflecting design criteria. The survey results indicate that rough estimation methods include the cost index, factor estimate, parameter estimate, cube method, unit method, cost weight, performance statistics, condition correspondence, and element (Kim 2018). Among them, both the unit area and element methods, which can reflect design criteria and can be used easily by co-housing association, were used in this study. To include the selected methods in the estimation plan, the area-related contents were examined in the previous cases and were converted into the elements of BIM (Table 1).

Table 1. Area-related elements of apartments and BIM conversion contents.

Classification	Area contents		BIM Conversion contents
	Before remodeling	After remodeling	
Household configuration	~10 pyeong	~10 pyeong	3D object by area

	~20 pyeong	~20 pyeong	
	~30 pyeong	~30 pyeong	
	~40 pyeong	~40 pyeong	
	~50 pyeong	~50 pyeong	
Building configuration	Horizontal length	Horizontal length	Building object
	Vertical length	Vertical length	
	Number of floors	Number of floors	Division of the building object
Complex configuration	Total floor area (ground)	Total floor area (ground)	Size restriction of the 3D object
	Total floor area (underground)	Total floor area (underground)	
	Underground parking lot floor	Underground parking lot floor	Underground parking lot 3D object

The household configuration is the information for dividing each household by size. Pyeong(1Pyeong equals 3.3 square meters) information is entered because each household exhibits different internal work and wall proportions. The building configuration is the information for distinguishing the information of each building. BIM allowed the user to create a three-dimensional (3D) model by drawing a construction area and input detailed information (horizontal length, vertical length, and the number of floors). The complex configuration is the information for distinguishing the information of the entire complex. This content can be obtained by adding all the data of the subunits in a detailed estimation. However, as this study addresses rough estimation, all data are not entered in the subunits. Therefore, the complex information was entered separately.

3.2. Design criteria of apartment vertical extension remodeling

Apartment vertical extension remodeling is rare because only a few cases occurred in the 2010s. Nevertheless, typical features for research could be found in several cases and data. It appears that the typical features occurred even though multiple construction companies had built apartments for multiple owners because the "wall column structure" was typically used for increasing productivity and reducing cost. No significant difference was found in the structure because the wall column structure was used. Despite similar forms, however, the number of design plans can be countless and unpredictable when they are changed by remodeling. Therefore, design criteria are limited by the surveyed contents. Design criteria have already been classified by Yoon (2013). As these design criteria only classified the types of remodeling that may exist, rough classification for rough estimation is required.

Hence, design criteria were derived by collecting the design criteria proposed by Yoon (2013) and previous cases. The derived design criteria were classified as follow Table 2.

Table 2. Apartment remodeling design criteria.

Classification	Detailed classification	Detailed option			
Area	Number of core extensions	None	1	2	3
	Degree of balcony extensions	None	0–3%	4–7%	8–10%
Parking lot	Ground parking lot extension	None	~50 cars	~100 cars	~150 cars
	Deck parking lot extension	None	1 floor	2 floors	3 floors
	Underground parking lot extension	None	1 floor	2 floors	3 floors
	E/V – underground parking lot connection	None	1 floor	2 floors	3 floors
Structure	Structural safety diagnostic rating	A	B	C	

	Structure type	Rahmen	Wall	Rahmen+wall	
	Bearing wall demolition	None	~10%	~20%	~30%
	Piloty utilization	No	Yes		
	Degree of seismic reinforcement	None	Small	Medium	Large
	Foundation reinforcement type	None	Micro	SAP	PHC
Others	Degree of interior remodeling	None	Low	Medium	High
	Degree of exterior remodeling	None	Low	Medium	High
	Landscaping range	None	Low	Medium	High
	Facility replacement range	None	Low	Medium	High
	Insulation construction range	None	Low	Medium	High
	Change in the use of PIT floor	Maintain	Change		
	Improvement of floor impact noise	None	Low	Medium	High
	Change in the heating system	Maintain	Change		

The design criteria were classified into area, parking lot, structure, others. For each classification, from two to eight detailed classifications exist. For each detailed classification, from two to four options are available. The area design criteria is related to the area of an apartment, and pertains to the number of added cores and degree of balcony extension. The parking lot design criteria includes ground and underground parking lots, and pertains to the degree of ground parking lot extension, installation of the deck parking lot, number of added underground parking lot floors, and connection of elevators to underground parking lots. The structure design criteria is related to the condition of a structure. It pertains to the structural safety diagnostic rating, structure type, degree of bearing wall demolition, Piloty utilization, degree of seismic reinforcement, and degree of foundation reinforcement. Moreover, design criteria are available for determining the levels of interior modeling, exterior modeling, and landscaping; meanwhile, other design criteria are used for examining facility replacement, insulation construction, change in PIT floor usage, improvement in floor impact noise, and change in heating system.

3.3. Construction cost change according to design criteria

Interviewing experts in apartment vertical extension remodeling regarding construction cost change reveals risks that are unidentifiable and different from those of new construction. This was attributable to insufficient samples as the cases were few and design criteria are many, as mentioned above, owing to the nature of remodeling and because the condition of the current building is different for each remodeling case. Among them, this study was conducted to emphasize that the construction cost varies significantly depending on each design criteria. In a similar previous study, Kang (2008) proposed the following as the characteristics of remodeling: the number of work groups that can be input, core type, elevator location, elevator availability, exhaust/pipe duct availability, width of building interior, balcony demolition, and demolition of nonbearing walls. Kang stressed that each element must be considered because it affects the process. This study attempted to quantify the increase and decrease in the construction cost of each design criteria proposed above through consultation with experts

		Staircase and Elevator extension(# of floors)			
		None	1	2	3
Demolition	Interior finish	⑦ 0.9~1.02	⑦ 0.9~1.02	⑧ 0.90~1.10	⑧ 0.90~1.10
	Frame	⑦ 0.9~1.02	⑦ 0.9~1.02	⑧ 0.90~1.10	⑧ 0.90~1.10
	Facility	⑦ 0.9~1.02	⑦ 0.9~1.02	⑧ 0.90~1.10	⑧ 0.90~1.10
	External wall	⑦ 0.9~1.02	⑦ 0.9~1.02	⑧ 0.90~1.10	⑧ 0.90~1.10

Fig. 1. Analysis of the construction cost variation by design criteria and work(part)

Fig 1 shows the analysis of construction cost variation by design criteria and work. In the table, the row represents design criteria and the column represents work. For example, to analyze the relationship between core extension and demolition-interior finish work, the corresponding cell is filled in with a relationship. In this study, the variation in the construction cost was analyzed using the table above, and the results were inserted to an estimation tool. The detailed introduction of the tool and its utilization method are described in Section 4.4.

3.4. BIM-based Estimation

In the construction industry, BIM has been applied to various areas recently, including the estimation area. Studies have been conducted to increase the accuracy of estimations by applying BIM to the estimations and studies to propose quantity calculation methods. In this study, it was emphasized that residents can easily utilize estimations for decision-making. When the estimation tool BIM is utilized, it is judged that the design contents are presented visually and the residents can set a design plan easily.

4. Concept of a BIM-Linked Rough Estimation Tool

Based on the aforementioned previous studies and surveyed contents, the method of linking each estimation with BIM was established. The aforementioned contents were included in the estimation method that involves the following procedure.

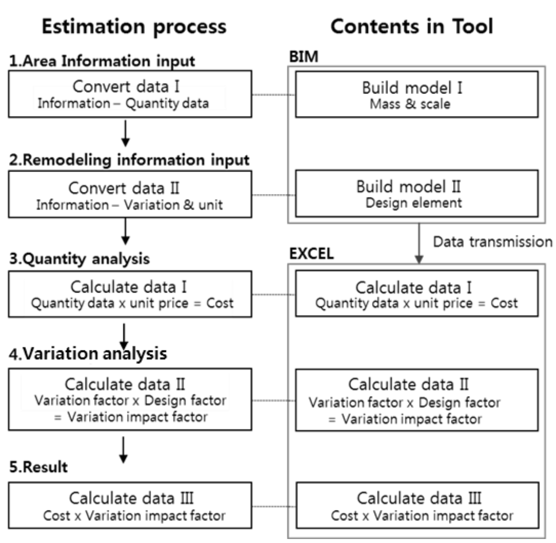

Fig. 2. Contents of the estimation process and the tool

Estimation was performed in the sequence of area information input, remodeling information input, quantity analysis, variation analysis, and result. (1) In the area information input, the information entered into the BIM model by the user is later converted into the quantity information for calculating construction costs by work. (2) In the remodeling information input, the information generated or entered into the BIM model by the user is converted into the cost variation value of each design criteria. (3) In the quantity analysis, the user inputs the unit price for each work. The construction cost is calculated through the operation of the entered unit prices and the quantity information converted in the area information input step. The contents from this step are processed in a separate Excel spreadsheet based on the contents extracted from the BIM model. (4) In the cost variation analysis step, the user evaluates the variation for each design criteria. The evaluated values are quantified and applied to the calculation of the construction cost. (5) In the result step, the construction cost obtained from the quantity analysis and the cost factor obtained from the variation analysis are subjected to an operation to calculate the final construction cost, which is displayed as a value per area. The concept of the tool created based on the contents above is introduced step by step in the next section.

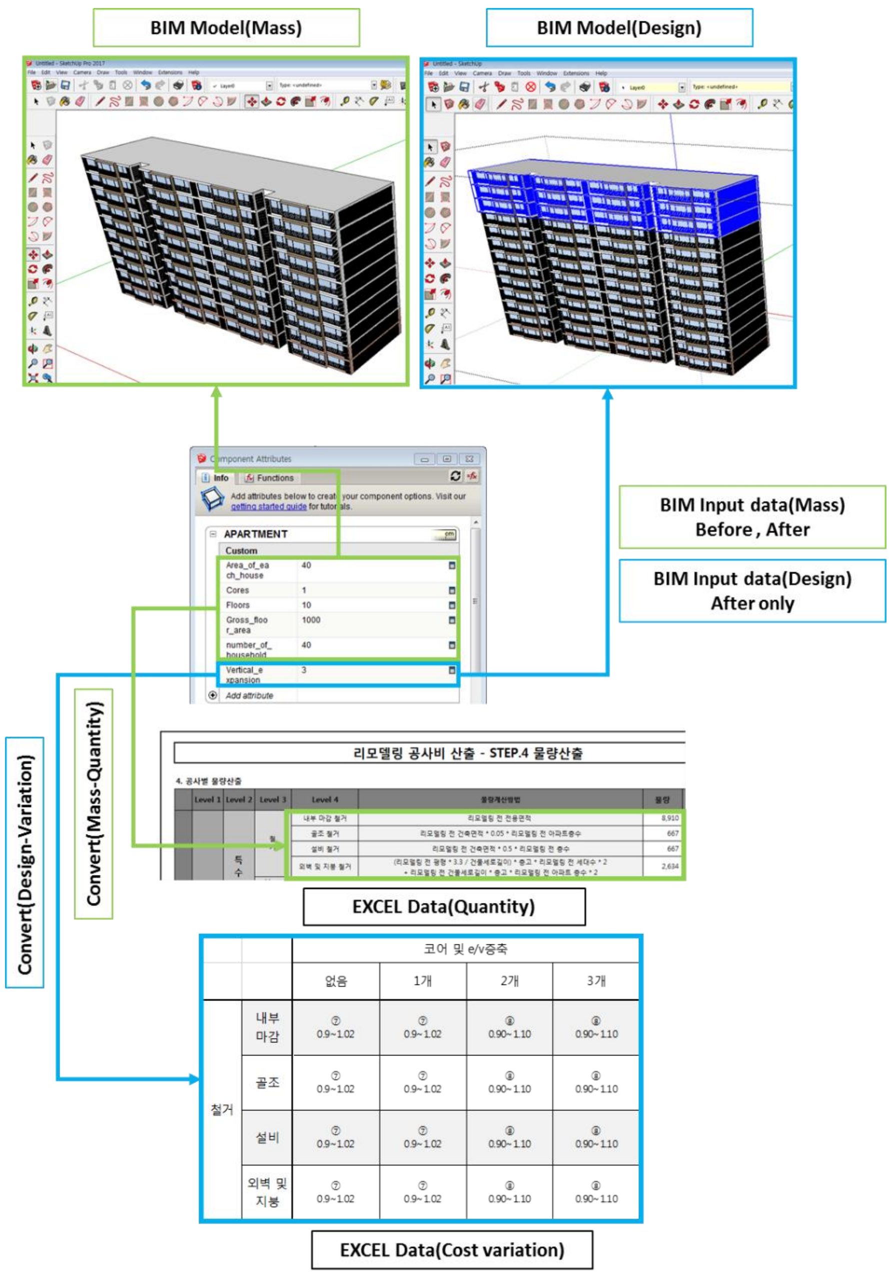

Fig. 3. Information input and information connection in BIM & EXCEL

4.1. Apartment project information input

In the " Apartment project information input " step, the user arbitrarily models the complex and enters the area-related information. The user goes performs the following steps for modeling.

Step 1. Enter the land area. Step 2. Adjust the shape of the land shown on the screen to match with the actual shape. Step 3. Draw the floor pattern of one apartment building on the land. Step 4. Enter the number of floors, number of households, and Area(Pyeong) information before and after remodeling into the pattern drawn in step 3. Step 5. A 3D object is built on the land according to the results of the input in step 4. Step 6. Repeat steps 3 to 5 until all buildings appear on the land. Step 7. Draw the pattern of the underground parking lot on the land. Step 8. Enter the number of floors and the area of the underground parking lot as well as the parking capacity before and after remodeling into the pattern drawn in step 7. Step 9. A 3D object is built under the land according to the results of the input in step 8. Step 10. Repeat steps 7 to 9 until all parking lots appear under the land.

Based on the information entered in this step, the amount of construction (construction area) is calculated by work. Work is divided into ground and underground, and 36 works exist. For example, the plastering area of one household is obtained through the "area of each household" of the entered information. It is multiplied by the "number of households" to obtain the plastering area of one building. This is multiplied by the number of buildings to calculate the amount of construction required in the project. In Figure 3, the information input window in the middle and the modeling in the top left corner correspond to the contents above.

4.2. Design criteria input

In the " Design criteria input " step, the design criteria of remodeling are added to the 3D model created in the previous step. The user adds the contents presented in Table 2 directly to the model. For example, the user can view the model with three floors as vertically extended when selecting "3" in the vertical extension. Upon the completion of this process, the 3D model created by the residents is completed. In Figure 3, the information input window in the middle and the modeling in the top right corner correspond to the contents above.

4.3. Quantity calculation

In the "quantity calculation" step, quantity is calculated by work based on the information entered into the model. Construction costs by work are calculated by multiplying the calculated quantity with the unit price.

In Figure 3, the quantity calculation table by work at the bottom corresponds to the contents above.

4.4. Construction cost variation by design criteria

To reflect the construction cost variation by design criteria to the estimation, the design criteria are quantified into probabilistic construction costs using a method known as Design criteria to cost method. In particular, the key to the quantification part was to reflect the fact that the correlations between each design criteria and work are different than the estimation method. For example, although vertical extension (1–3 floors) was performed, the cost of the finishing work did not vary significantly whether one or three floors were extended vertically. Meanwhile, the foundation work and reinforcement work exhibited significantly higher construction costs. Reinforced concrete also demonstrated an increase. An extreme example is the vertical extension of an underground parking lot. For this vertical extension, the cost of earthwork is highly likely to increase significantly owing to bedrock as the depth of extension increases. For the foundation work, the construction cost increases significantly as well. Among the cases collected for this study, the average construction cost was 1.5 times higher than other cases, and the reason was earthwork.

As shown in the examples above, each design criteria affects the construction costs by work with different degrees and possibilities.

To distinguish these, the degrees and possibilities of influence are divided in the following figure.

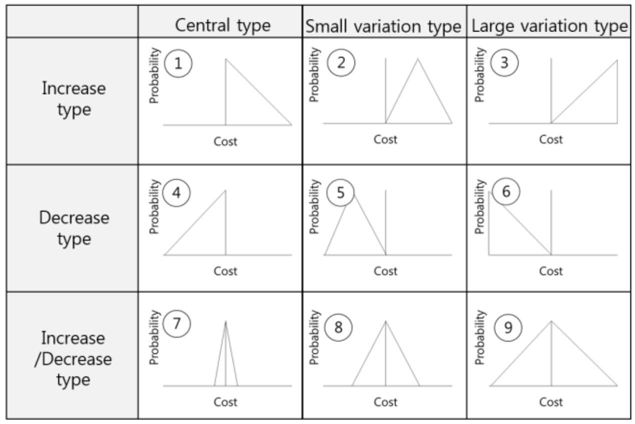

Fig. 4. Analysis of construction cost increase/decrease types according to the probability-cost

The construction cost types were divided into the increase type, decrease type, and increase/decrease type according to the increase or decrease in the construction cost, and into the central type, small variation type, and large variation type according to the variation degree of the probability. For example, for the increase type-central type (number 1), the construction cost is likely to increase, but the possibility is low. For the decrease type-small variation type (number 5), the construction cost is likely to be lower than the estimated cost and the possibility is highly likely to be lower than the estimated. The increase/decrease type-large variation type (number 9) is the pattern obtained when the estimated construction cost is high. The construction cost can be higher or lower than the estimated cost, and the increment or decrement is extremely. Next, the construction cost variation range is calculated. The variation amount was between zero and 2 with respect to 1. For example, when the minimum value is 1, the maximum value is 2 and the median value is 1.5 for the increase type-small variation type; the construction cost increases or decreases by 1 or 2 times in the low probability and is 1.5 times higher in the high probability. The minimum, maximum, and median values were calculated for the construction cost patterns obtained above. The next step is to convert each probability distribution range derived in the form of a triangular distribution into the value range by substituting the construction cost. In the previous step, construction costs by work were calculated by inputting the area information and design information of apartments. Changes in construction costs by design criteria were applied to the calculated construction costs. For example, if the cost of reinforced concrete work is calculated to be KRW 1 million and the construction cost range has the minimum value of 1, maximum value of 2, and median value of 1.5 for the increase type-large variation type, the construction cost is calculated to be between KRW 1 and 2 million. In the final step, the construction costs calculated as ranges are converted into probability distribution forms using @RISK software to introduce the probability concept. In the previous step, only the construction cost range of KRW 1 and 2 million was calculated. The concept that "the median value of 1.5 has the highest probability" was applied to this step.

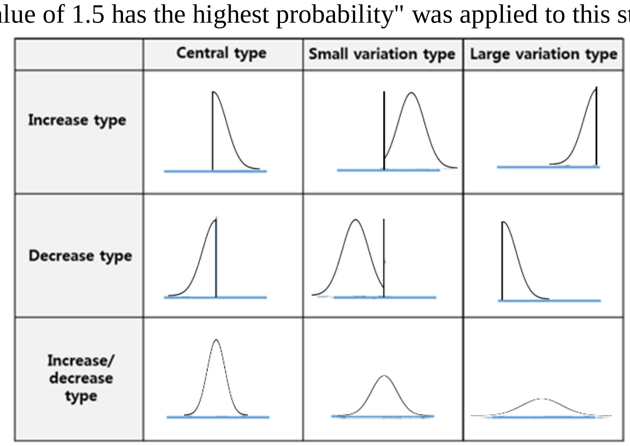

Fig. 5. Construction cost type by design criteria with the probability concept

Hence, the built-in functions of @RISK were utilized. Consequently, the minimum value, maximum value, and mode could be obtained for each work according to the probability. The final construction cost can be obtained by adding the calculated construction costs of all works.

4.5. Range construction cost calculation

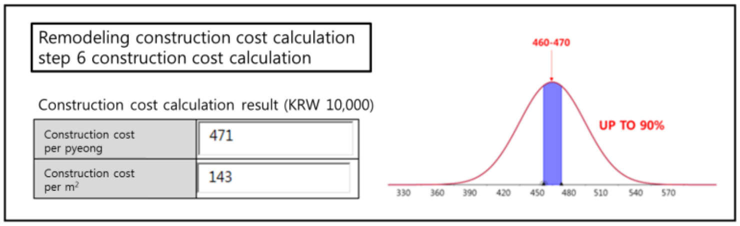

Fig. 6. Final construction cost calculation screen

In the "construction cost calculation" step, operation is performed based on the values entered in the steps above to display the calculated construction cost on the screen. The construction cost per area is displayed for the residents to easily judge the appropriateness of the cost. In addition, the range of the construction cost is calculated through probability statistics to increase its reliability.

5. Conclusion

In this study, the problem in estimating for large-scale remodelling apartment buildings has been identified. Also, a new approach in estimating the projects by integrating BIM models with design criteria. Hence, it was possible to positively reflect the design criteria that were not reflected in previous estimations, and the estimation accuracy is expected to be increased. Specifically, the design criteria of remodeling has been derived, and the degree of influence of each design factor on each type of work has been analyzed. This is meaningful in that the existing practitioners have transformed what expert perceived through experience and intuition into specific figures. In addition, the range value is derived as numerical value that the range of each design element can be different. The residents would be able to prevent project duration extension arising from communication problems with the estimation company if this tool were used. Moreover, the tool will be highly beneficial for the decision-making of the resident union by facilitating the decision-making of the residents themselves on the design. If further remodeling cases are analyzed in the future, the accuracy of estimation and usability of the results of this study is expected to be further improved.

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Development of planning-stage feasibility-assessment model for extension remodeling projects of old apartment buildings

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Abstract

The government has continuously amended and developed laws for the vitalization of remodeling apartment buildings against the backdrop aging buildings. Despite such efforts, however, extension remodeling has not yet been used. Even though there are various issues causing this shortcoming, the present study focused on the fact that there is no instrument for reliable feasibility analysis and decision-making in the early stage of remodeling projects, thus proposing a remodeling project feasibility-assessment model. Generally, a feasibility (profitability) judgement is made after a design proposal is derived, and because decision-making for the implementation of remodeling projects is determined at the initial stage of implementation committee, a feasibility analysis model for projects at the planning stage is necessary. In this work, construction cost, project cost, financial expenses, and general sales revenues are calculated using remodeling project variables derived through existing apartment complex information, consultation, and research, and an algorithm was developed that can calculate approximate return on investment and the share of expenses of resident union members using the calculation results. In addition, the applicability of the model was tested by applying the developed early stage project feasibility analysis model to three cases already implemented. When the model was applied to three cases, the errors between the values predicted by the model and the actual values of the cases were 5% or less, indicating high reliability of the model. The model is expected to become a useful tool in practice if the applicability of the model is further proven by increasing the number of cases in the future. The project feasibility-assessment model developed in the present study will enable smooth implementation of projects by supporting residents' rapid decision-making. Moreover, if the model is variously applied by region, it is also expected to contribute to the policy establishment of local governments that identify the scale of apartment complexes in which extension remodeling projects are possible and support the remodeling.

Keywords: Remodeling of old Apartment, Extension remodeling project, Feasibility-assessment Model

1. Introduction

The ratio of people living in apartment buildings in South Korea is significantly higher than in other countries, and apartment buildings account for almost 60% of all housing[1]. The massive supply of apartment buildings to provide housing since the 1980s and apartments built due to the construction of new cities in the metropolitan area has given rise to problems from aging. These problems include not only the physical aging of structures and facilities but also reduced convenience of existing buildings due to technological and economic growth. It is clear that the aging problem

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is not only a problem for residents but is also an issue at the national level, because the number of aged apartments has grown to over four million units and will continue to grow.

1.1. Background

So far, the solution for the aging problems of apartment buildings has been reconstruction, but the number of complexes that can improve the residential environment through reconstruction is greatly reduced due to government policies such as reconstruction control, though remodeling projects are expected to increase.

Remodeling projects can be classified into general maintenance remodeling, customized remodeling, and extension remodeling, depending on the scope of remodeling. Extension remodeling, which is the target of the present study, focuses on the overall performance improvement of existing housing by extending household size or increasing the number of households through vertical or horizontal extension of building, building annexes, or partial reconstruction[2].

As extension remodeling is allowed under the 2012 revision of the housing act, project feasibility is greatly improved[3]. In particular, the amendment made possible the extension of three floors in the case of apartment buildings for more than 15 stories (up to 15% of the number of existing households). Despite the revision of the act, however, extension remodeling projects are making slow progress due to various problems in implementation. Accordingly, among various problems, the present study paid attention to the fact that there is no instrument for reasonable project feasibility analysis and decision-making in the early stage (before the design phase) of vertical extension remodeling projects.

The goal of this study was to provide union members with an efficient decision-support model at the planning stage of remodeling projects by calculating the contract area after remodeling based on only the basic information of the complex and calculating the share of the expenses by type (apartment size) of complex and return on investment (ROI). If it is possible for residents to make a rough decision on remodeling feasibility at the planning stage, it will have a considerable positive influence on saving project cost and initial bonding among residents through rapid decision-making and the implementation of the project. In addition, such an approximate feasibility model is expected to make it possible for the government and local governments to predict the overall demand for old local apartment buildings, establish local policies and master plans for the increasing problems of old apartment buildings, and provide basic data for policy decision-making.

1.2. Methodology

The research procedure was conducted in the following order: (1) review of domestic and foreign literature and previous research related to feasibility judgment methods, (2) selection and derivation of variables to be considered in predicting the feasibility of extension remodeling projects, (3) establishment of the overall feasibility assessment model process considering the influence of selected variables on feasibility, (4) presentation of assessment indices and decision-making methods of feasibility analysis to be presented as the resulting value, and (5) the verification of the effectiveness of the model. The procedures and methods are presented in Fig. 1.

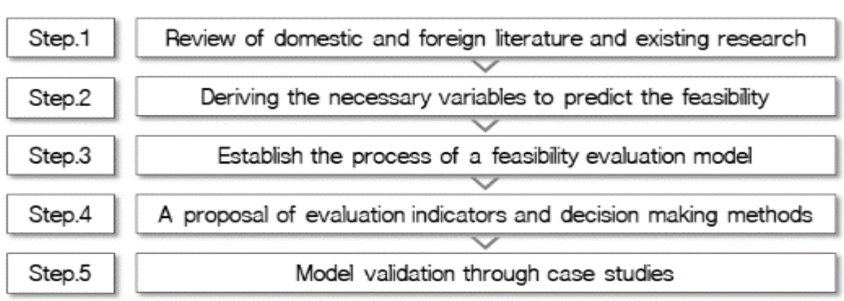

Fig. 1. Research procedures and methods.

2. Literature review

The feasibility assessment model of remodeling projects has been tried in various ways, as shown in Table 1.

Table. 1. Studies of remodeling feasibility assessment model

Author	Characteristic
Yoon and Park (2001)[4]	Survey on the factors affecting residents' consciousness to remodeling and affecting profitability of remodeling in Seoul and Gyeonggi-do
Lee, Cha and Lee (2003)[5]	Analysis of importance of assessment factors for economical assessment of remodeling business
Hwang and Song (2004)[6]	Analysis of the importance of economic value added through the survey of experts in construction and remodeling
Yoo, Kim, Yoon and Yang (2006)[7]	Analysis of profitability factors, assessment criteria, and profitability prediction model of remodeling business
Kim, Cha, Shin and Kim (2013)[8]	Proposal of a business-oriented decision-making process by using the proposed model based on a model that can predict revenue and expenses
Yoon, Shin and Kim (2016)[9]	Estimation of the construction cost of the area to estimate the value of the end-of-life, after-tax asset, development cost, and estimated contribution

When these studies are analyzed and summarized, the majority of previous studies conducted to develop feasibility models are classified roughly into two types: (1) calculation of construction cost according to the correlations among project variables based on the results of previous project cases and (2) research on feasibility assessment methods and setting variable values to develop a model. There is no research on extension remodeling, which is the target of the present study; however, because these two types of previous studies were conducted on customized remodeling projects.

In addition, the project expenditure costs, such as planning cost and construction cost, cost of extension remodeling projects are very sensitive to area changes because such projects can involve bearing wall demolition, structural reinforcement, and horizontal and vertical extension. Consequently, approximate estimation method based on the prediction of the contract area of the project and cost per unit area is essential for initial feasibility analysis.

Therefore, a feasibility assessment method based on ROI by the calculation of contract area and share of expenses by apartment size after remodeling appears to be more rational than feasibility analysis derived from correlations among feasibility variables based on previous project cases.

3. Feasibility assessment model

Feasibility assessment model can more accurately assess feasibility when construction cost is calculated by considering factors such as the size and type (corridor access type, flat-type, and tower-type) of existing apartments, location of the elevator(s), demolition of the bearing walls, structural type, foundation type, and the cost of structural reinforcement according to ground condition.

The present study cannot determine factors such as the removal of bearing walls or structural reinforcement cost according to ground conditions until detailed design proposals is available. This is because this study assesses feasibility before the design (proposal) is available in the initial stage of remodeling project, and it is very difficult to individually calculate construction cost according to the size and type of existing apartments, because there have been few cases of vertical extension of buildings until now.

Accordingly, the present study applied the recent average bid price (construction cost) per unit area of vertical extension remodeling work of constructors[10]. This construction cost per unit area is the actual bid price of constructors, which includes the size, type, and structural reinforcement cost of apartment houses, and expert consultations: KRW 5.3–5.7 million / pyeong (about 3.3 m^2) was applied depending on the floor-area ratio.

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Based on the feasibility concept of an extension remodeling project, the development of the feasibility model presented in Fig 2 is possible.

ROI and feasibility are calculated by previous value (A), future value (A'), and the union share of the expenses (Y). The union share of the expenses is determined by project cost (W) and total revenue from general sales (X), and these two are calculated in relation to the area of the space that is changed by the remodeling project—i.e., the (future) contract area. Accordingly, the most important factor in the feasibility assessment in the initial stage of the project, which is before the finalization of remodeling design (proposal), is accurately predicting (future) the contract area.

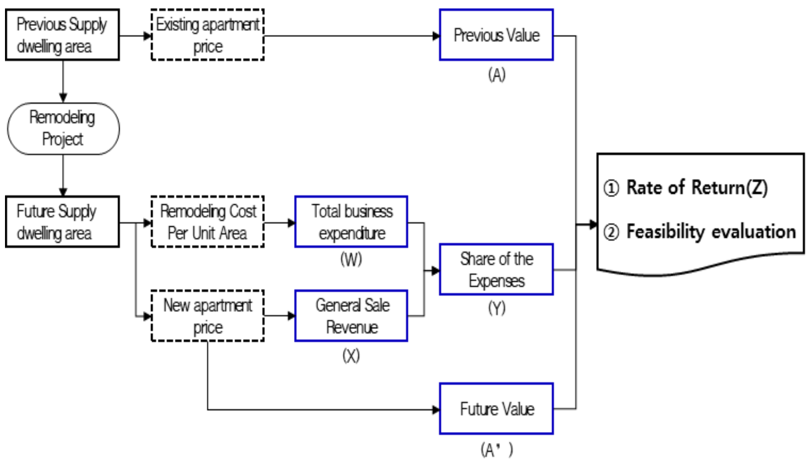

Fig. 2. Feasibility evaluation model process

4. Program Development

4.1. Program operation procedure

The presented feasibility assessment model is built on Excel, and the model can be divided into three modules: input, analysis, and decision-making. The operation procedure of the model is shown in Fig 3.

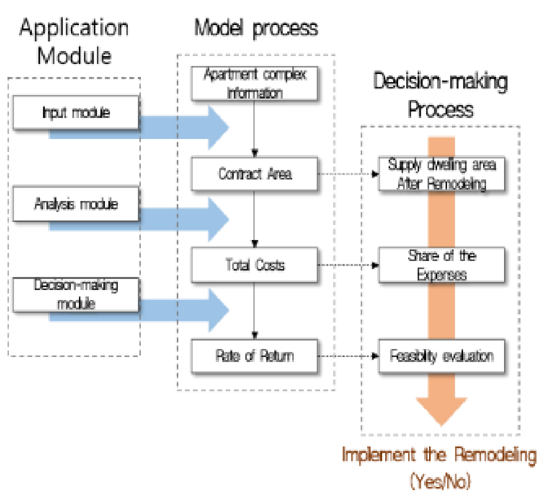

Fig. 3. Operation procedure of feasibility assessment model

In the input module, variable factors that have significant influence on feasibility are directly entered, or default values are chosen after entering (previous) apartment complex information, and go through a stage in which fixed factor values are confirmed.

The goal of the analysis module is calculating the total project cost by calculating contract area using the information of the input module. The total project cost is the total share of the expense of the union calculated by adding construction cost, other project cost, and difference between purchase and sales revenues.

The decision-making model helps to make decisions on the implementation of remodeling through three steps. The first step determines whether the feasibility analysis exceeds 100% (i.e., creates profit); the second step determines whether the allowed share of expenses of union households satisfies the expected share of expenses of the model; the third step assesses whether the proposed project is superior / good / average / poor depending on the level of ROI.

If there is an unsatisfactory item among the three steps above, a satisfactory value should be obtained by modifying the value of a variable factor of the input module. The roles of the three modules of the feasibility assessment model discussed above are presented in Table 2.

Table. 2. Detailed classification of feasibility assessment models

Division	Input module	Analysis module	Decision-making module
Step. 1	Input Actual Data	Calculate contract area	Feasibility evaluation
Step. 2	Variable Data Setting	Calculate future value	Rate of return
Step. 3	Identify Fixed Factor Data	Calculate total cost	Share of the Expenses

4.2. Program verification

Extension remodeling generates profits from the sales of the added apartments, unlike customized remodeling or reconstruction. Therefore, the physical verification of feasibility assessment is possible through comparison to the constructed complex after signing the contract between the constructor and the union. The physical verification of the union’s share of the expenses and feasibility assessment is impossible, because currently there has been no case of extension remodeling.

Accordingly, attempts were made to increase the completeness of feasibility assessment through the verification of the contract area. As mentioned above, the contract area is judged appropriate to determine the accuracy of the model, because construction cost and project cost, and financial expenses for them are calculated by contract area. Accordingly, three complexes with different characteristics in terms of number of households, floor-area ratio, and apartment size among the remodeling complexes in the architectural design review stage were selected and used in the simulation.

The overview of verified complexes is presented in Table 3.

Table. 3. Overview of the verification case-study

Division	(Existing) Floor Area Ratio	Number of Households	Type	Characteristics
Seocho-gu 'A'	268.50%	239	89, 92 (m^2)	High Floor area ratio, Small scale complex, Medium type
Gangnam-gu 'B'	248.85%	138	92 (m^2)	Medium Floor area ratio, Medium scale complex Medium type
Gangnam-gu 'C'	182.81%	2,015	43, 53, 63 (m^2)	Low Floor area ratio, Large scale complex

Small type

The feasibility assessment model was developed by applying the existing value, actual value after remodeling, and predicted value of the model to three cases of complexes in architectural design review. The variable factor value of simulation was calculated as a default value, and the results are shown in Table 4.

Table. 4 Overview of the verification case study

Division		Seocho-gu 'A'	Gangnam-gu 'B'	Gangnam-gu 'C'
Floor area ratio	Existing data	268.50%	248.85%	182.81%
	Actual data	399.68%	387.76%	289.13%
	Prediction data	402.75%	373.28%	274.22%
Number of Households	Existing data	208	120	1,753
	Actual data	237	138	1,988
	Prediction data	239	138	2,015
Number of parking spaces	Existing data	134	55	489
	Actual data	286	152	2,450
	Prediction data	287	166	2,418
Exclusive Dwelling Area	Existing data	16,921.24 m²	10,121.70 m²	71,852.90 m²
	Actual data	23,501.78 m²	14,117.34 m²	100,512.08 m²
	Prediction data	23,685.80 m²	14,170.38 m²	100,594.06 m²
Dwelling Public Area	Existing data	1,921.24 m²	1,257.15m²	21,893.34 m²
	Actual data	4,799.73 m²	3,552.32 m²	47,084.24 m²
	Prediction data	4,835.42 m²	3,235.64 m²	42,572.76 m²
Service Facilities Area	Existing data	437.81 m²	1,206.75 m²	5,250.57 m²
	Actual data	1,537.17 m²	1,711.39 m²	9,264.97 m²
	Prediction data	984.22 m²	1,439.55 m²	5,502.48 m²
Underground Parking Lot Area	Existing data	3,702.17 m²	-	1,960.40 m²
	Actual data	9,221.97 m²	5,691.98 m²	86,156.02 m²
	Prediction data	10,906.00 m²	6,308.00 m²	91,884.00 m²
Contract Area	Existing data	22,979.65 m²	12,585.60 m²	100,957.21 m²
	Actual data	39,060.05 m²	25,073.03 m²	243,017.31 m²
	Prediction data	40,411.44 m²	25,153.57 m²	240,553.30 m²
Error in contract area(%)		**3.46 %**	**0.32 %**	**-1.11%**

The results showed that exclusive dwelling area and dwelling public area are highly accurate because they are obtained by limiting to floor-area ratio, but other common-use areas and parking lot areas showed some difference from the actual contract areas.

The accuracy of contract area is, however, the key point in this model, since the construction cost is calculated per contract area when a constructor is actually making a contract with a union. Simulation results showed high accuracy of the contract area, with an error rate of less than 5% (the contract areas of the three complexes were assessed to be 103.46%, 100.32%, and 98.99%). The reasons for the errors were that (future) floor-area ratio and the (future) number of parked cars per household were predicted values, and the corrected values of (future) other common-use areas and (future) underground parking lot area do not perfectly reflect the areas after remodeling. The accuracy of contract area will increase as more cases are accumulated in the future.

5. Case Application

The developed feasibility assessment model was applied to Gumi-dong, Bundang-gu, Seongnam-si, Gyeonggi-do. The average feasibility of remodeling of this dong with 18 apartment complexes is "insufficient," with 103.1%. Even among them, areas with better location requirements showed "average" feasibility, which indicates the necessity of remodeling strategies and policies for each region in small units based on regional differences, as seen in the feasibility map below.

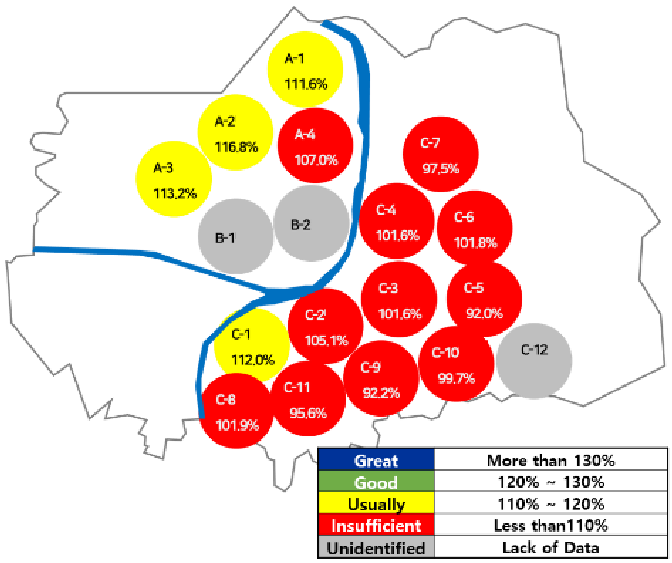

Figure. 4. Feasibility map applied to Gumi-dong

6. Conclusion

This study was motivated by the necessity of the overall feasibility analysis of extension remodeling projects of old apartment buildings. Accordingly, it presents a model with which overall feasib ility and ROI analyses are possible so that sound judgments can be made on whether to implement extension remodeling projects before the design phase, and the model was implemented using the Excel program.

The model was applied to three cases of complexes that actually implemented projects, and the analysis results were compared to actual outcomes. The results showed that the model was working as originally intended, and because the errors of the results were within 5%, the possibility of its practical use is high if the model is consistently complemented with new data.

In addition, feasibility was examined by applying the model to one dong (town) in Bundang-gu. As such, the model is judged to significantly contribute to the decision making of union households if it is widely applied to old apartment complexes. Moreover, if it is applied to local governments by region, the model is expected to contribute to the identification of the scale of apartment complexes for which extension remodeling projects are possible and the policy establishment of local governments that support the remodeling.

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Effectiveness of Drone-Based Photogrammetry for On-Site Quantity Assessment

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Abstract

Drone-based surveying using laser scanning with LIDAR has been routinely used in heavy construction to produce high-quality topographical data with increased grid/mesh density when compared to traditional surveying. Differences between pre-construction conditions and post-construction topographical scans thus provides a basis for identifying the work performed, measuring progress and managing progress payments. The technique has demonstrated cost-effectiveness with less physical effort and less time becoming the go-to technology on large unit-price heavy construction projects. The approach is not routinely used on smaller projects partially due to the cost of acquiring the technology or outsourced services. Alternative technologies are desired which could benefit smaller and potentially more diverse construction activities. One promising approach involves using reality capture based on high-resolution imagery. This approach processes a cloud of geolocated imagery to develop virtual models which can then be integrated and analyzed through a BIM platform. Drones-based imagery through off-the shelf unmanned autonomous vehicles (UAV's) provide the ideal input for this reality capture techniques. The reliability of the resulting models is unknown, however, and research was performed to identify the reliability of the technique to determine on-site volumetric and area quantities. Various off-the-shelf UAV's (drones) were evaluated and statistical techniques were employed to quantify the reliability of the resulting models. Regression was used to extract data obtained through systematic trials to site-level applications. Results are presented and future directions are outlined and discussed.

Peer-review under responsibility of the scientific committee of the Creative Construction Conference 2019.

Keywords: construction, UAV, drones, estimating, quantity surveying

1. Introduction

Quadcopter unmanned aerial vehicles (UAV's or drones) are widely used among hobbyists around the globe. Within the professional communities, such drones have also found a place for surveying and construction applications. For surveying, drones coupled with LIDAR units provide high-speed accurate data collection which otherwise would be cumbersome to collect using traditional surveying methods. In construction, drones are used to provide additional imagery throughout the life-cycle from concept through completion: imagery which can provide net benefit in the decision-making process. Imagery captured through drones provides significant value in conceptual and preliminary

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design. Construction professionals can use imagery to layout construction sites and monitor job-site activity. Likewise, owners can use likewise use the imagery for marketing and business development and drone-based imagery has proven to be highly effective in real estate development marketing and sales. Drones have also found use for construction oversight and for inspection purposes by contractors, owners and consultants, and government regulators. The use of drones as part of the construction delivery process has provided significant value and promises to become more commonplace as time progresses as the value of aerial imagery continues to increase. It is expected that the aerial imagery, either through still photos or video, will be a standard and expected tool for documenting, communicating and recording current conditions with little expense.

Using drones for imagery requires very little investment and there are no substantial barriers for entry into the marketplace as a user or an outsource provider. Use of drones can begin with low-priced commercial off-the-shelf quadcopter drones which today provide sufficient photographic and video resolution and capture capabilities at high-definition or 4K resolutions. Software and programming enable make today's drones very easy to fly and there is little learning curve necessary to become proficient. Drone operation will require licensure in many areas but such licensure is not overly burdensome for small operations.

While using drones for video and imagery is a low-cost endeavour, using drones for more sophisticated purposes, such as drone-based surveying, requires much higher-priced equipment. For large projects, drones fitted with LIDAR can provide significant cost-savings despite the significantly higher cost of the drones and the associated equipment when compared with low-cost consumer drones. For small projects, the use of such equipment may be or may be perceive to be cost prohibitive. It is known that photogrammetry can be applied with good results and the technique is marketed by commercial entities and outsourced solution providers whom affirm the reliability and effectiveness. To capitalize upon this assertion, a research endeavour was undertaken with freshman-level undergraduate students in the construction engineering and management program at the University of Delaware. The goal of this research was to explore the reliability of photogrammetry for quantity surveying and to provide a platform for freshman-level student to be exposed to research activities and the use of technology for construction purposes. The result of this research effort are provided in this paper. Known applications of drones will be summarized followed by a discussion of the research study and the results. The examination will conclude with a discussion of opportunities for further research and application of drones to improve construction project delivery.

2. Consumer and Commercial Drones Utilized

Unmanned aerial vehicles (UAV's) as mentioned are pervasive and are used in many different industries. There are numerous manufacturers of UAV quad-copter drones and each drone has different advantages and disadvantages in term of range, flight time, carrying capacity and so on. DJI drones have captured the majority of the consumer market and were chosen for the purposes of this study. The drones used for this study are shown in Figure 1 and included DJI Sparks, Ryze Tello's, and a DJI Phantom. From a practical perspective, any drone with good photographic and videographic capabilities would be equally effective for the purposes of this research. The DJI drones are all GPS guided while the Tello's are camera guided. Commercial drones with increased size, power and capabilities, are available in the marketplace. These include DJI Matrice and Inspire drones which increase the capabilities and may be incorporated in future research efforts. They were not required for the purposes of this research. Likewise, fixed wing drones, which are particularly useful for highway projects were significant range is required, are beyond the scope of this study.

3. Uses and Applications of Drones in Construction Practice and Research

In order to get a better idea of how drones are being used in practice, a brief literature review was performed coupled with a search of drone providers web-marketing services for construction. There are a wide variety of examples of aerial imagery for construction purposes such as the construction site shown in Figure 2A. There are numerous examples of drone imagery online for sites around the country. Roof inspection has found a niche in construction because of its obvious benefits to reduce risk and to give easier access. Roof imagery is shown in Figure 2B with highlighted problem areas. Roof areas can also be determined using photogrammetry, as marketed by several companies including dronedeploy.com. Drone providers also provide inspection services using thermography and photogrammetry, such as is shown in Figure 2C and 2D. New applications also continue to emerge and there are really exciting developments when AI is coupled together with drone imagery, such as the real-time pattern recognition capabilities shown in Figure 2E, which identifies vehicles and vehicle types in real time on-site.

Figure 1: Drones used for the research study

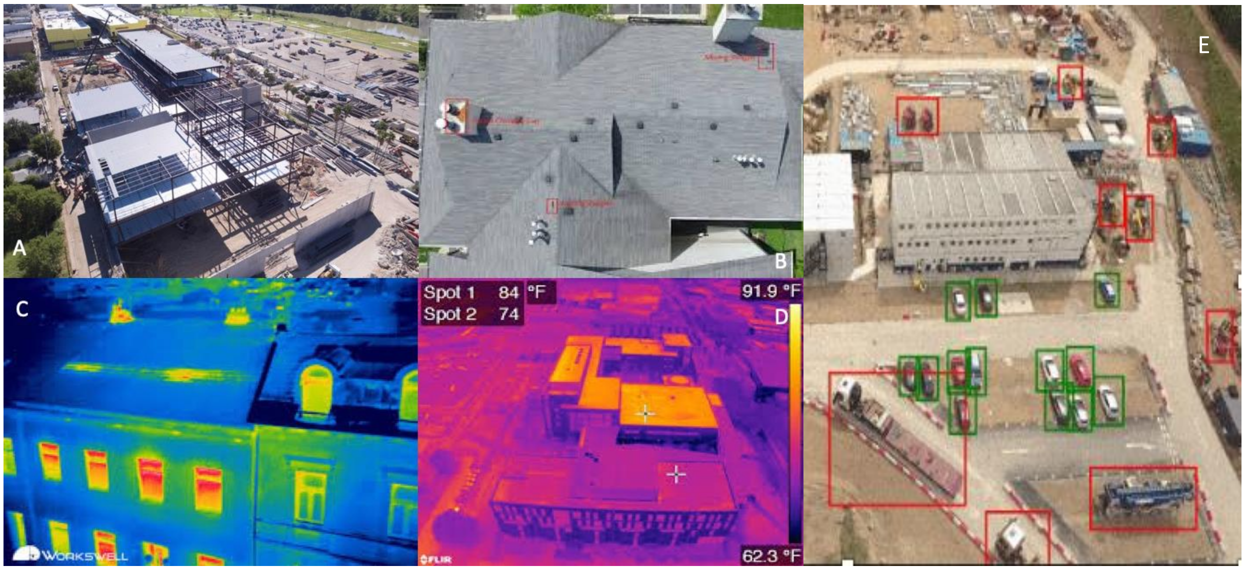

Figure 2: Typical drone imagery used for construction (source: globalvideohq.com, FLIR, workswell.com, accessed 4/15/2019)

An information survey of sites identified revealed the following primary uses of drones for imagery, as previously presented and discussed in [1]:

- Construction progress photography and development of promotional and marketing materials – This could be for documenting progress or static imagery could be "turned into a time-lapse video or GIF' [2]
- Preconstruction planning and evaluation visual surveying of site terrain – "Before ground is broken and after it is cleared, you can get a detailed aerial view of the proposed construction site to use for logistics and production planning." [2]

- Visual inspection and auditing – With line-of-sight consumer drones, video can be live-streamed allowing real-time inspection of conditions on the job-site. This could be used as an effective tool to evaluate construction conditions in hard to reach areas to ensure quality and successful completion/progress of activities.
- Safety improvement – Drones can also be used to evaluate workers in hazardous areas removing the inspector from the hazardous area and providing frequent real-time feedback. This can mitigate risks and cut costs [3]
- Volumetric measurement – "using accurate aerial photogrammetry techniques, large areas (2D and 3D) can be measured to within CM accuracy. This can be accomplished quickly, cost effectively and with minimal disruption to the day to day workings of the site." [4]
- 3D Modelling – Drone based LIDAR can be used for developing digital terrain models and digital elevation models. Photogrammetry can also be utilized and a study on commercial drone industry trends revealed significant increases in the use of drones to develop 3D models. [5]

Navigant, whom performed a survey on drone opportunities and uses within construction, identified progress evaluation, inspection, marketing and logistics/production planning as the highest potential applications. [6] Realized potential is lagging as the actual use of drones still has to catch up with market opportunities.

A variety of research activity has been identified. This includes research on visual inspection of civil infrastructure systems. [9] The researchers found significant promise in the use of drones for concluded that drones, "for inexpensive, easy, and quick documentation [but] … that there are still numerous open problems for further research" [9]. Research has been performed on image processing and the use of drones for seismic risk assessment and post-earthquake reconnaissance [10], for construction safety [11], for mapping and earthquake response [12], for visual inspection in a wide-variety of applications, for security and materials management [13], and for performing construction activities [14]. There are significant opportunities for advancing research on the application of drones building upon these and other research activities. These opportunities increase exponentially when looking beyond the use of drones simply for visual documentation and the coupling of new technologies with more advanced and powerful drones could result in a paradigm shift in sectors of construction project delivery.

4. Research Study

As mentioned, LIDAR can be used to provide highly accurate topographical surveys which can then be used to identify quantities. Alternative techniques using photogrammetry are also touted as reliable approaches for quantity surveying on construction sites and are routinely used to identify volumes of soils/spoil and areas of roof by numerous service providers. This research was formulated to evaluate the effectiveness of using low-cost commercial off-the-shelf drones to identify quantities in terms of reliability. The research was structured not only to obtain results but also to involve freshman-level construction engineering students in research and to get them thinking of how to use common-place technology for construction benefit.

The research began looking at the reliability of identifying the volume and the surface area of a known object. The object chosen was a skylight on the University of Delaware campus at McKinley Plaza. The skylight is shown in Figure 3a. Drone imagery was captured using DJI sparks as the Tello imagery was not geolocated and thus could not be used for photogrammetry. Geo-tagged and geo-located images were captured for multiple trials, which were then processed using Autodesk ReCap to "capture reality" and develop point-cloud imagery and a virtual model. To develop this model, surfaces are dissected and stitched back together to form the 3D image. Dissected imagery for the skylight is shown in Figure 3b while the 'stitched' 3D model is shown in Figure 3c. The reflections on the glass panels are slightly distorted but the panels themselves are planar and not distorted as may be seen in the representation in 3b.

The effectiveness of the reality capture software is a function of many different variables, including the number of pictures taken and the number of different perspectives, the resolution of the pictures, and so on. The DJI spark shoots 1080p video with a 12MP 4k CMOS 1/2.3" sensor. The drone produces 3968 x 2976 resolution pictures with a 4:3 aspect ratio. The Phantom also provides this imagery with a 1" CMOS sensor, which would give better image quality. The study was conceptualized to compare results from Sparks and Phantoms to evaluate the impact of sensor size and image resolution; however, due to time constraints, only the Spark imagery was used. This study thus evaluates the reliability with respect to the high-resolution 12MP imagery, which is a lower-bound of commercial drones expected to be used for ReCap purposes. The number of images taken and the perspectives of the images are also factors. For the purposes of this study, images were taken around the entire object at multiple elevations. Thirty trials images were used for development of each model in the trials to provide consistency and enough imagery to presumably develop a sufficiently accurate point cloud.

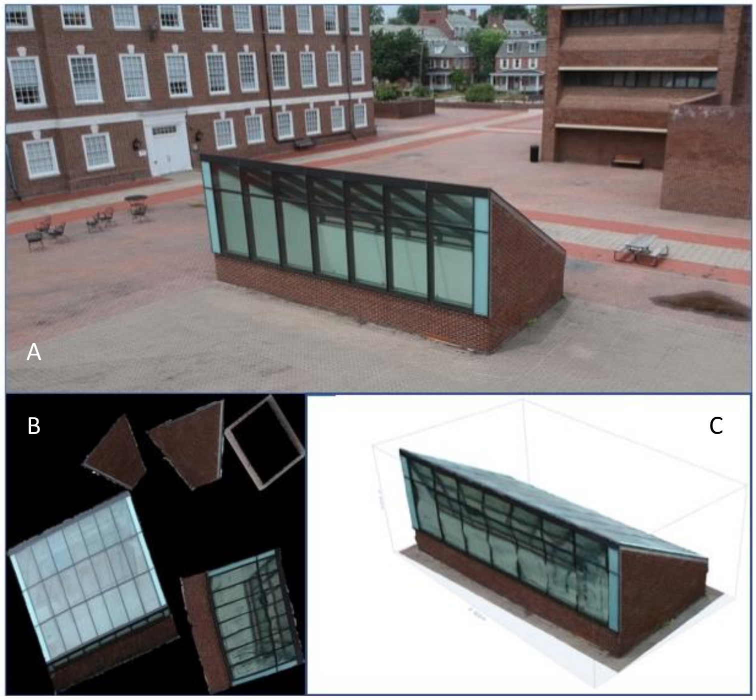

Figure 3: McKinley skylight and ReCap representations

The study began with examination of the McKinley skylight and successively reduced the size of the object to determine whether reliable results can be generated for smaller objects on a construction site. With the case of the skylight, it was found that depending on the time of day and the orientation of the sun, reflections off the glass could trick the software into inaccurately assuming voids in the three-dimensional space. In effect, a reflection could be interpreted as a tunnel progressing through the glass panels. Imagery used for the trials was thus taken during periods were direct sunlight was not causing reflections. Following the skylight, trials were performed on shipping boxes of decreasing size, such as those shown in Figure 4.

Converting the imagery to point-clouds was a time-consuming process using educational licenses and 5 trials were performed for each object. For the objects, the calculated volumes and surface areas are as shown in Table 1. The skylight was 5 meters x 10 meters in plan area with a varying height from 2 to 4 meters nominally. As-built dimensions differed from plan and actual field-surveyed values were utilized. Measured dimensions of the boxes are shown in Table 1.

Table 1: Skylight and Boxes - Actual Measurement

Object	Surface Area		Volume		Dimensions
Skylight	202.3856	(sq. meters)	153.05472	(cu. meters)	5m x 10m x 2-4 m nominal
Box 7	17,448	(sq. cm)	153,252	(cu. cm)	66cm x 54cm x 43cm
Box 6	14,136	(sq. cm)	75,888	(cu. cm)	102cm x 31cm x 24cm
Box 5	8582	(sq. cm)	47616	(cu. cm)	64cm x 31cm x 24cm

Figure 4: Boxes used to evaluate quantities

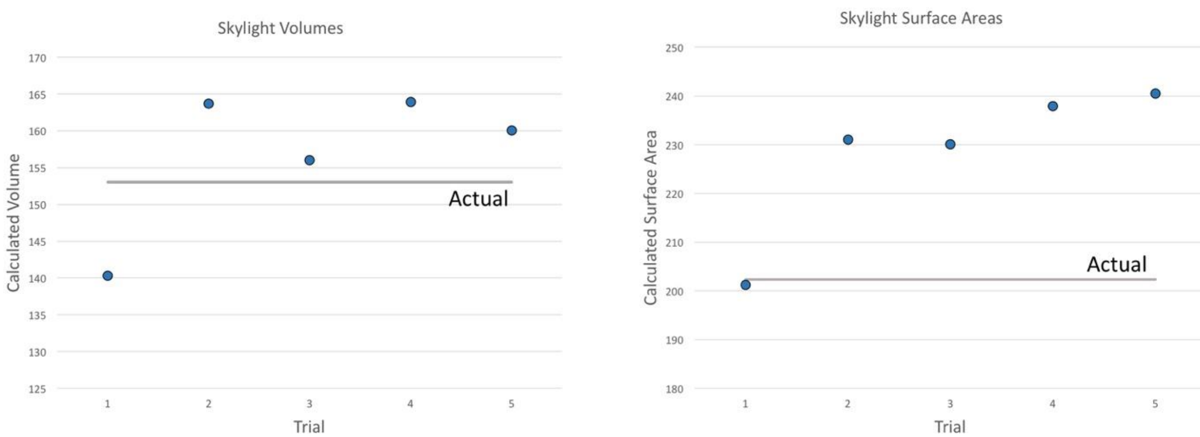

Figure 5: Trial values for the Skylight volume and surface area compared to actual values

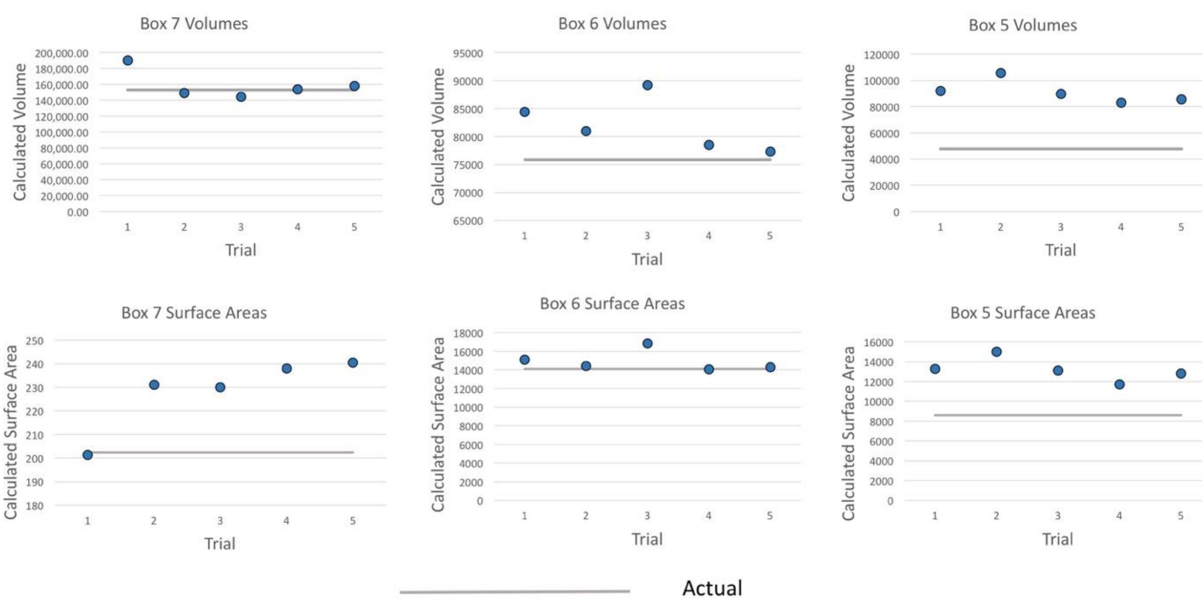

Figure 6: Trial values for the box volumes and surface areas compared to actual values

Table 2: Skylight and Boxes – Differences between the trials and the actual values

Trial	Volumes				Surface Areas			
	Skylight	Box 7	Box 6	Box 5	Skylight	Box 7	Box 6	Box 5
1	-8.3%	24.2%	11.2%	92.8%	-0.6%	24.1%	7.0%	54.4%
2	6.9%	-2.6%	6.7%	122.2%	14.2%	3.7%	2.0%	74.6%
3	1.9%	-5.7%	17.5%	88.2%	13.7%	1.3%	19.3%	52.7%
4	7.1%	0.3%	3.5%	74.1%	17.6%	6.6%	-0.6%	36.4%
5	4.6%	3.2%	1.9%	79.5%	18.8%	9.3%	1.1%	49.4%
Average	2.4%	3.9%	8.2%	91.4%	12.7%	9.0%	5.7%	53.5%

5. Conclusions

Unmanned autonomous vehicles (UAV's), otherwise known as drones, are becoming increasingly common in construction and there are a wide variety of uses for the technology, which has been explored. Research continues to expand the use of drones in the industry and one would expect to see more applications for drones emerge in the near future. One such use is the application of drones to determine on-site quantities. This is routinely done with LIDAR units and differential approaches communicating with base stations for increased survey accuracy. This works well for large projects but there is also an opportunity to employ drones on small projects using photogrammetry. This is being done by solution providers but is seldom employed by small contractors. This research was initiated to explore the use of photogrammetry with low-cost commercial quadcopter drones. A skylight element on campus was chosen due to its accessibility and known properties. Trials were performed to determine the adequacy of photogrammetrically determine surface areas and volumes developed using Autodesk ReCap. Smaller volume objects were added to determine the adequacy of the approach for various size objects which may be found on a construction site. When the overall volume of the object was under 75,000 cubic-centimetres, trial results were highly overestimated and unreliable. Limited trials were performed and additional tests will be done in the future to develop more statistically reliable results.

Acknowledgements

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Emergent subcontracting models and owner involvement in selecting subcontracting strategies and participants in the U.S. construction industry

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Abstract

Prime contracting models for a wide variety of Project Delivery Methods (PDM) have been described with great detail in the practice-oriented and academic literature. However, the same depth of understanding about contractual relationships between general and specialty contractors is less known, especially as specialty contractors are being increasingly involved in earlier project phases. The objective of this research is to describe subcontracting models, owner involvement scenarios, and their variations across the United States. Results of a nationwide survey and follow-up semi-structured interviews with industry practitioners indicate many subcontracting models are currently in use and that project owner involvement is widely variable. Presentation attendees should expect to gain a greater understanding of each of the identified subcontracting models as well as to learn the advantages, disadvantages, regional variations, and owner involvement under each.

Peer-review under responsibility of the scientific committee of the Creative Construction Conference 2019.

Keywords: subcontracting model; nationwide; variations.

1. Introduction

Subcontracting practices greatly influence contractual responsibilities and construction activities as subcontractors generally execute 60 to 70 percent of the total project activity [1]. These subcontracting practices might vary depending on whether the project delivery method (PDM) and procurement policies selected allow for participants to be added to the project within a wide range of contractual options. Selecting the right subcontracting practice may promote the integration of the process deployed by contracting parties, increase reciprocal trust and achieve better project performance. Another possible improvement is the development of long-term associations between general contractors and subcontractors once they have contractually established the precise hierarchical structures for successful project performance.

Given these potential benefits, understanding the scope of emerging subcontracting practices is one way construction participants can try to improve project performance. To provide better information, this paper presents a brief synopsis of the findings from a U.S. nationwide survey and follow-up set of semi-structured interviews. The results are evaluated to identify the correlations between samples, to detect regional subcontracting patterns, and to identify potential new subcontracting practices.

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2. Subcontracting practices

This research expands upon a previous study that identified and evaluated subcontracting practices in the state of Washington [2]. The previous study identified five different subcontracting practices. Figure 1 shows the following five subcontracting models found by Osmanbhoy: 1) traditional subcontracting (TS); 2) traditional subcontracting with design assist (TS-DA); 3) design-build subcontracting (DBS); 4) integrated design-construction subcontracting (IDCS); 5) integrated specialty work subcontracting (ISWS).

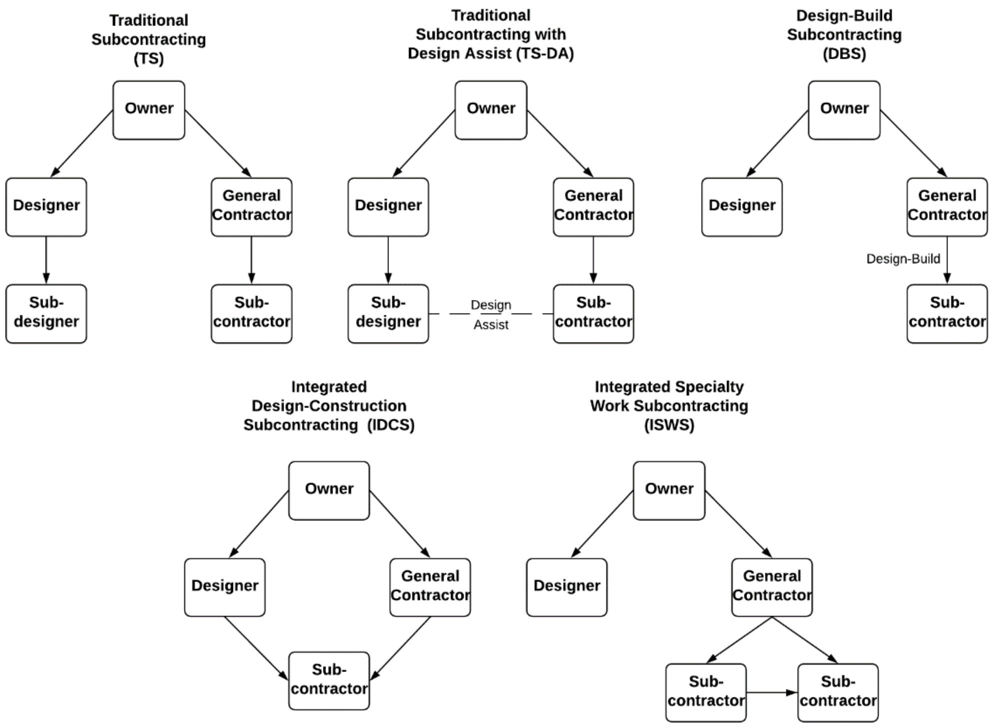

Fig. 1. Subcontracting practices.

2.1. Traditional subcontracting (TS)

This subcontracting practice is based on the segregation of design and construction activities into two separate supply and contracting chains. This practice generates two linear phases where the first phase is the development of drawings and specifications by the designer without the support of the contractor. Once these documents are used to secure prices from competing contractors, the second phase is focused on implementing construction activities [3,4]. As a result of these practices, the specialty expertise on each side (design and construction) work under isolated conditions where the direct link is their prime.

2.2. Traditional subcontracting (TS-DA)

Design-Assist practice mediates the segregation typical of TS by creating a path for collaboration between specialty designers and specialty contractors. This new collaboration path is described as the improvement of design and constructability concerns throughout the early involvement of specialty contractors in design activities. Although the specialty contractor is participating during the design process, this practice is not intended to transfer design liabilities to specialty contractors [5]. Under this collaborative design agenda, construction participants are expected to achieve better project results in cost, time, and quality.

2.3. Design-Build Subcontracting (DBS)

Design-Build (DB) has been described extensively in the literature. However, DB has two different scenarios to involve specialty contractors during the project stages. The first scenario centers on the work of architects/engineers and general contractors; this joint-venture business association will design and provide the specification parameters to all specialty contractors to complete the design process together. This scenario sees the occurrence of DB integration at the prime contracting level and has been described in the literature. The second scenario focuses on the integration of DB principles at the subcontracting level and is novel; It relies on the selection of specialty contractors that will deliver both design and construction services within their specialty based on the specialty contractor's knowledge and solutions [6]. The last scenario resembles Osmanbhoy's DBS practice.

2.4. Integrated Design-Construction Subcontracting (IDCS)

The IDCS practice is one example of collaborative contracts and practices where the lead designer and general contractor have distinct contracts with the same specialty contractor who develops design documents and controls construction activities. IDCS practices have not been well-identified in the literature, but there are some insights which describe the potential links with this practice. For example, one case study details IDCS practices that were applied to a design-to-fabrication methodology for structural rebar using building information modeling (BIM) tools under a Construction Manager/General Contractor contractual strategy [7].

2.5. Integrated Specialty Work Subcontracting (ISWS)

The ISWS practice is focused on the development of collaborative methods to improve time and cost requirements. This development is created by all the specialty contractors using the detection of critical tasks that may quantify the correct amount of effort, participation, and resources in each construction activity for every subcontractor. This specialty contractor supportive agenda allows the existence of terms like reliability and contribution which generate revenue rewards that can be shared among team members [8].

3. Research methodology

A mixed methods approach was selected in order to provide a more nuanced view on subcontracting strategies and increase the generalizability of the results. The sample population for the study was obtained from multiple sources including the American Subcontractor Association (ASA), the Associated General Contractors of America (AGC), and from appropriate research team member contacts. A list of over 800 individuals was developed from these sources.

The first phase of data collection focused on obtaining information through an online survey instrument. The main goal of the survey was to establish contact with individuals in the dataset and to identify their key characteristics. The survey for both general and specialty contractors were both divided into two parts. The first part focused on obtaining general company information (i.e., type, size, market experience, and value), interviewee position, and professional contracting experience. The second part centered on gathering enough information to elucidate contractual approaches for each participant type.

In the second phase of data collection, semi-structured interviews were conducted. Based upon the response to whether or not respondents would like to be contacted for a follow-up telephone interview, the research team evaluated survey response data before selecting candidates. This allowed the research team to ensure interviewees would possess the required experience in and knowledge of subcontracting practices and models. The interviews were focused on obtaining all the insights from the participants related to the five key subcontracting practices, potential variations, and owner involvement.

4. Data collection and analysis

4.1. Online survey

The survey was sent to 847 participants from 598 different companies; a total of 170 participants completed the survey representing a 20.07% participation rate. We excluded from the analysis seven survey response sets because they were incomplete. Tables 1, 2, and 3 show the survey top three answers from all the participants in three different sections: general information, general contractor, and specialty contractor segments. The online survey information was categorized following US Census Bureau Divisions.

Table 1. General information segment. **QUESTION**	**FIRST RESPONSE**	**SECOND RESPONSE**	**THIRD RESPONSE**
Location	West North Central (46%)	West South Central (18%)	South Atlantic (14%)
Participants' Experience	More than 15 years (61%)	Between 5 and 15 years (18%)	Between 2 and 5 years (13%)
Participants' Position	Executive (51%)	Project Manager (17%)	Estimator/ Project Eng (13%)
Current Position Experience	From 0 to 5 years (41%)	More than 15 years (35%)	Between 5 and 15 years (23%)
Largest Contract Size	Between 1 and 10 M (43%)	Between 10 and 50 M (27%)	Between 50 and 250 M (11%)
Contractual Role	Prime Contractor (61,37%)	Subcontractor (102, 63%)	N/A
Participants' Involvement	Fully (54%)	Somewhat (38%)	Aware (6%)
Participants' Company Size	Between 10 and 50 M (33%)	Less than 10 M (21%)	Between 50 and 250 M (17%)

Table 2. General contractor segment.

QUESTION	**FIRST RESPONSE**	**SECOND RESPONSE**	**THIRD RESPONSE**
Adopted PDM^M	Design-Build (65%)	Design-Bid-Build (63%)	CM at Risk (62%)
Subcontracting Selection Criteria	Lowest Responsible Bid (85%)	Best Qualifications (82%)	Business Relationships (67%)
Multiple Contractual-Relationship	Yes (57%)	No (24%)	Unsure (19%)
Other Contractual Parties	Prime Contractor (70%)	Owner/Client (49%)	Designer (45%)

Table 3. Specialty contractor segment.

QUESTION	**FIRST RESPONSE**	**SECOND RESPONSE**	**THIRD RESPONSE**
Subcontractor Selection Criteria	Business Relationships (62%)	Best Qualifications (54%)	Lowest Responsible Bid (51%)
Procurement Approach from GC	Business Relationships (72%)	Lowest Responsible Bid (71%)	Best Qualifications (60%)
Contractual Bounded Parties	Prime Contractor (95%)	Owner/Client (65%)	Specialty Contractor (39%)
Multiple Contractual-Relationship	Yes (50%)	No (47%)	Unsure (3%)

4.2. Follow-up interview

Based on the selection participants criteria from the Research Methodology chapter, the expected response for the follow-up interviews was set at 36 interviews - 13 General Contractors and 23 Specialty Contractors. After three invitation cycles, 20 participants (13 General contractors and 7 Specialty Contractors) confirmed and completed the follow-up interview, resulting in a final response rate of 55.55 percent. Table 4 and 5 summarize all the key comments from the follow-up participants about the subcontracting practices, variations, and owner involvement.

The subcontracting models that have were explained to the participants were generally accepted and widely used by most participants. For this reason, the interviewees did not introduce any new subcontracting practices as expected in the research objectives. In contrast, the research identified small variations that can be used to augment existing models in several ways. These include four variations to Integrated Specialty Work Subcontracting strategy and modification to the Design-Build Subcontracting strategy. Table 4 indicates these modifications where all the secondary bullets are placed. Figure 2 graphically illustrates these five variations.

Table 4. Follow-up interview subcontracting model and variations findings.

SUBCONTRACTING MODEL	FINDINGS
Traditional Subcontracting (TS)	• Public Projects: 80 to100% use • Private Projects: reduction from 80 to 50% use • Industry standard • GC complete control over SC • Lack of involvement in design stages • Low bid mentality
Traditional Subcontracting Design-Assist (TS-DA)	• It represents 10 to 15% use • Related to a pre-selected piece of equipment • Increase building coordination • Few SCs are capable of performing this method • Command chain issues • Risk of shifting design liabilities to SC
Design-Build Subcontracting (DBS)	• It represents 10 to 15% use • Under traditional DB increases to 30% use o Lead designer inclusion in DB entity • SCs are fully committed to design process • Design flexibility to start construction faster • Better design and cost control • Design stage could be time-consuming
Integrated Design-Construction Subcontracting (IDCS)	• Less than 10% use • Participants limited knowledge • Participants pointed to the West Coast as the zone where this method happens • Highly specialized products and early design associations among construction parties • Collusion and communication issues.

Integrated Specialty Work Subcontracting (ISWS)	• GCs have a 50% acceptance rate
	• SCs have a 100% acceptance rate
	• Allows few responsibilities points due to the avoidance of bringing external contractors
	• Risk of delaying activities due to scope interference
	• GCs develop solutions to avoid this supportive agenda
	    o Strict contractual arrangements
	    o GC control over repetitive activities using specific specialty trades
	• SCs develop solutions to execute specialized tasks
	    o Inclusion to sub-subcontractors (third tiers) to one subcontractor
	    o More than one link among subcontractors using sub-subcontractors

Table 5. Follow-up interview comments for IPD and owner involvement findings.

SUBCONTRACTING MODEL	FINDINGS
Integrated Project Delivery (IPD)	• IPD practices in Missouri and Colorado • Revenue based on sharing contingency of saving and losses • The revenue sharing is the incentive to improve coordination and collaboration • Successful IPD projects have the right combination of people • Owners must keep the economic factor alive to make IPD projects attractive
Owner Involvement	• GCs have more opportunity to participate in the owner selection process of PDM and procurement • SCs could participate if owners select them early in the process • Owners' request to be taught is the opportunity to create sophisticated owners who understand the construction industry better

5. Conclusions

The ability to generalize the research finding to all regions of the U.S. is somewhat limited due to regional bias. Analysis of the online survey and follow-up interview data show that the majority of survey participants were from the West North-Central and West South-Central regions while interviews were generally concentrated in the central region of the United Stated. Nevertheless, the online survey and the follow-up interviews both exhibited a strong participant understanding of project delivery methods. In addition, research participants were adept at differentiating between various subcontracting strategies. However, within each PDM and procurement strategy, regional variations did exist. Divisional samples had some degree of equilibrium among traditional practices (i.e., DBB, lowest responsive bid, and no multi-contractual arrangements) and more collaborative techniques (e.g., DBB, CM/GC, business relationships, and best value), some regions were found to work with more traditional methods than others. Participants from the Pacific, Mountain, and West North Central divisions of the U.S. Census Bureau reported using more collaborative and multi-contractual practices. The other regions demonstrated a more equilibrated sample, with a tendency toward traditional methods. Given the regional bias, the research can infer two conclusions. First, all five subcontracting models studied to address the most common scenarios, and characteristics are familiar to the nationwide participant sample. Second, the need to find better contractual arrangements creates effective variations from the original models, and as such subcontracting practices are dynamic by nature.

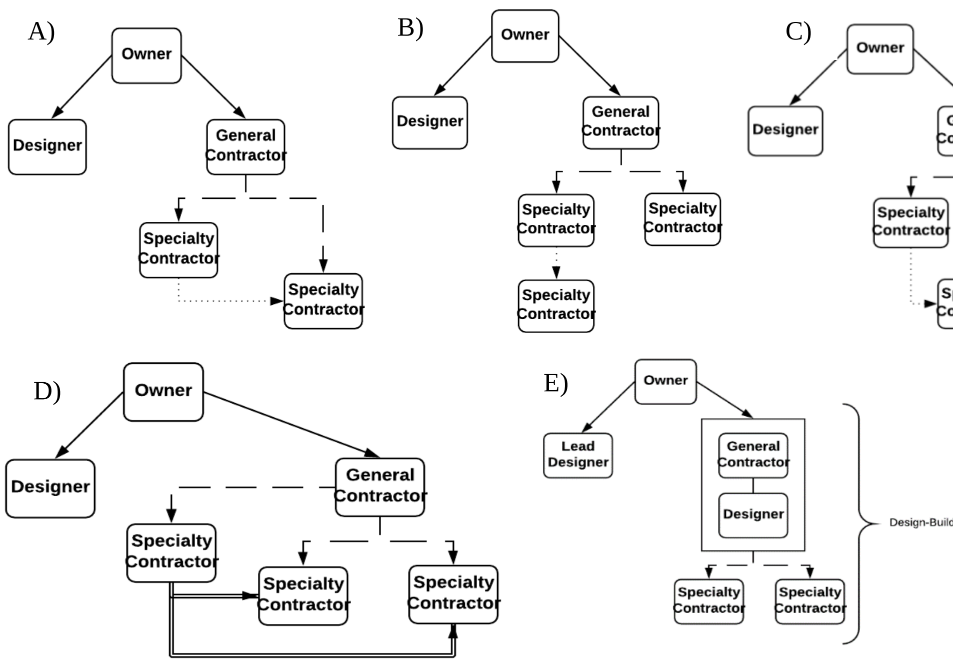

Fig. 2. A) ISWS variation 1; B) ISWS variation 2; C) ISWS variation 3; D) ISWS variation 4; E) DBS variation-confirmation 1.

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Estimating occupancy- and space utilization rates in non-residential buildings using planned-activity data

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Abstract

Occupancy- and space utilization rates in non-residential buildings are often used as a metric for building efficiency. However, these rates are typically measured only for buildings already in use, at a stage where optimizing the size or layout of a building to improve efficiency becomes increasingly challenging and expensive.

The aim of this exploratory study is to describe a method for estimating the occupancy- and space utilization rates in non-residential buildings using planned-activity -based data. Such a method enables the client to obtain estimates of the occupancy- and space utilization rates already during the design phase of a building, when size- and layout -related changes are more easily and affordably executable. The method is best applicable to buildings with a high degree of usage predictability, such as educational establishments.

The research design of the study is based on a descriptive embedded single case study. In effect, the activity-based occupancy- and utilization rate estimation method is applied in the context of evaluating a building layout during the design phase of a school building project in Southern Finland. The main finding of the study is that an ex-ante estimation of occupancy and space utilization rates facilitates in optimizing the building layout during the design phase to improve its efficiency during the usage phase. Moreover, the results suggest that the developed method helps clients to improve project scope management and building value in use.

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Keywords: building efficiency; building value; occupancy rate; project scope management; space utilization rate

1. Introduction

Two of the key metrics in measuring the efficiency of a non-residential building are its occupancy- and space utilization (O&SU) -rates. Occupancy rates measure the ratio between the total time of a space being in use, and its total availability, while space utilization rates refer to the average capacity use of a space, while occupied. Both of these rates have an impact on several stakeholders of the building: O&SU -rates above optimal levels can lead to dissatisfaction of tenants as well as increased maintenance costs for the building owner On the other hand, if O&SU -rates fall below their target levels, the return on investment for the owner can fall short of expectations. It should thus be of mutual interest for all stakeholder groups of, that the occupancy and space utilization rates of commercial buildings are given appropriate emphasis already during the design phase of a building.

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However, in practice, it is usually only after the completion of a building that O&SU -rates are evaluated. While the scope of a building project, along with its layout are naturally designed with the intention of ensuring optimal O&SU -rates, no actual estimates are usually calculated ex-ante. In effect, it is exceptional that building investment feasibility studies and project briefs contain quantitative analysis or measurable targets for building efficiency [1]. Based on the authors' experience, this can lead to unrealistic expectations of building efficiency, as well as bottleneck spaces, and imbalanced occupancy rates between spaces of a building. In the case of a school building, neglecting ex ante O&SU -rate estimation while designing the layout can lead to the following issues among others:

- The number of teaching areas needed is calculated directly based on the number of student groups, leading to vacant classrooms, low occupancy-rates and poor building value
- Extracurricular, and possible after-school rental usage of spaces is overestimated, lowering both the occupancy as well as the space utilization rates and decreasing the net present value of the building
- The special spatial needs of external users of the building are not taken into consideration

The aim of this paper is to describe a procedure that allows for an ex-ante estimation of the O&SU-rates of a building, by a method of using planned activity -data. We describe applying this method to a real case, a school building project in the city of Järvenpää, Finland, with a population of nearly 40 000 inhabitants. The case was selected because it aims to create a new school building project model for the public sector. In fact, the project is a national benchmark project for new practices in school building construction.

The empirical contribution of the paper is in the application of activity-based O&SU -rate estimation method in the context of evaluating a building layout during the design phase of a school building. By describing a new method for activity-based O&SU -rate estimation, this study increases understanding of how the occupancy- and space utilization rates can be estimated and utilized in non-residential buildings using planned-activity -based data.
The remainder of this paper is structured as follows. After a brief clarification of the terminology, we will review earlier academic literature on the subject. Next, we present and discuss the benefits of the planned activity -based method, followed by an introduction to the case project, a school building in Järvenpää, Finland. We describe the implementation of the planned activity -based method in our case example in detail. Finally, the results and findings from the implementation are then presented and summarized, along with their implications to the stakeholders of the case project.

2. Defining occupancy and space utilization -rates

The terms "occupancy" and "space utilization" in the context of non-residential real estate are widely used in both academic literature, as well as within practitioners within the industry. However, their definitions seem to vary depending on the context, and the terms are in effect mostly used in commercial settings. For example, Statistics Finland (Tilastokeskus) defines occupancy rates for hotels as the number of rooms used in a given month, by the number of rooms available for the month [2]. Terms are less frequently applied in the context of schools, workplaces, and other similar settings. Thus, in order to provide some clarity, we define the terms "occupancy rate" and "space utilization -rate" as follows:

- The occupancy rate of a space as the ratio of the time in use, divided by the total availability time
- The space utilization -rate as the average percentage of capacity used when the room is occupied.

To illustrate, if a space with a capacity of 20 people and daily availability of 8 hours were in use for 4 hours per day by a group of 15 people, the occupancy rate of this space would be 50%, with a space utilization rate of 75%.

3. Literature Review

Given the importance of the subject, we find it interesting to note that O&SU -rate estimation methods during the design phase of a building have not received much attention in academic literature. This lack of attention can likely be attributed to the fact that the usage patterns of many non-residential buildings are difficult, if not impossible predict at a sufficiently precise level at an early phase, making ex ante O&SU-rate estimation obsolete. However, there are many cases where the amount and type of activities can be forecasted with a high level of certainty. A notable example of such a case are educational establishments.

In Finland, determining the required scope and layout of an educational building has typically been calculated using a direct driver-based approach, using area-ratios related to the desired student capacity [3,4,5]. However, the planned activity -based approach in the context of designing a building layout is also well documented, and presented thoroughly by Pennanen [6]. Pennanen presents an example case of designing a layout for a school building by taking advantage of the high degree of predictability of activities within educational establishments. Pennanen provides an extensive discussion on the benefits of applying an activity-based method to designing school buildings, such as its ability to adapt to special spatial needs of the establishment. Unsurprisingly, our findings on the benefits of applying activity-based methods in evaluating a school building layout share similar characteristics.

While numerous papers about building occupancy and its prediction methods have been presented in academic literature, most of these papers focus on predicting occupancy rates of existing buildings, using sensory data and advanced methods such as machine learning techniques [7,8]. One typical use case of such predictions is the optimization of the HVAC-system of a building, leading to reduced energy costs [9,10]. Per the knowledge of the authors, no prior research has been conducted on applying an activity -based approach to building layout evaluation through O&SU -rate estimation.

4. Methods for O&SU-rate estimation

4.1. Activity- vs. Driver-based methods

As opposed to using conventional, driver-based methods, the method presented in this paper can be classified as activity-based. The main difference between activity- and driver-based methods is that the former links the the underlying drivers of a process to the available resources by first converting the drivers to a list of activities, and ultimately allocating activities to available resources. The latter, on the other hand, links drivers directly to the available resources through multipliers. Figure 1 illustrates the differences between the two methods.

As already mentioned, in general terms, driver-based methods link the underlying drivers directly to available resources. In our example case of designing and evaluating the layout of a school building, a driver-based approach would entail linking the number of students in a school directly to available classrooms. Evaluating the layout through a driver-based O&SU-rate estimation procedure would entail calculating the ratio between available resources (i.e. number of distinct space types) and the driver (number of students), and comparing the result to a benchmark.

While this driver-based approach is simple to use, and typically used in designing layouts of school buildings, it is rather cumbersome when working in the opposite direction, and evaluating the efficiency of the proposed layout. Firstly, the obtained result ratios are rather uninformative by themselves, since they must first be compared with benchmark ratios from previous projects. Secondly, information on the goodness of the benchmark ratios (i.e. the corresponding O&SU-rates) might not be easily available, and their validity and reliability is difficult to assess. Thirdly, the driver-based approach cannot easily take into account special requirements, such as the above average need for certain types of teaching facilities in a school with an unusual or emphasized curriculum.

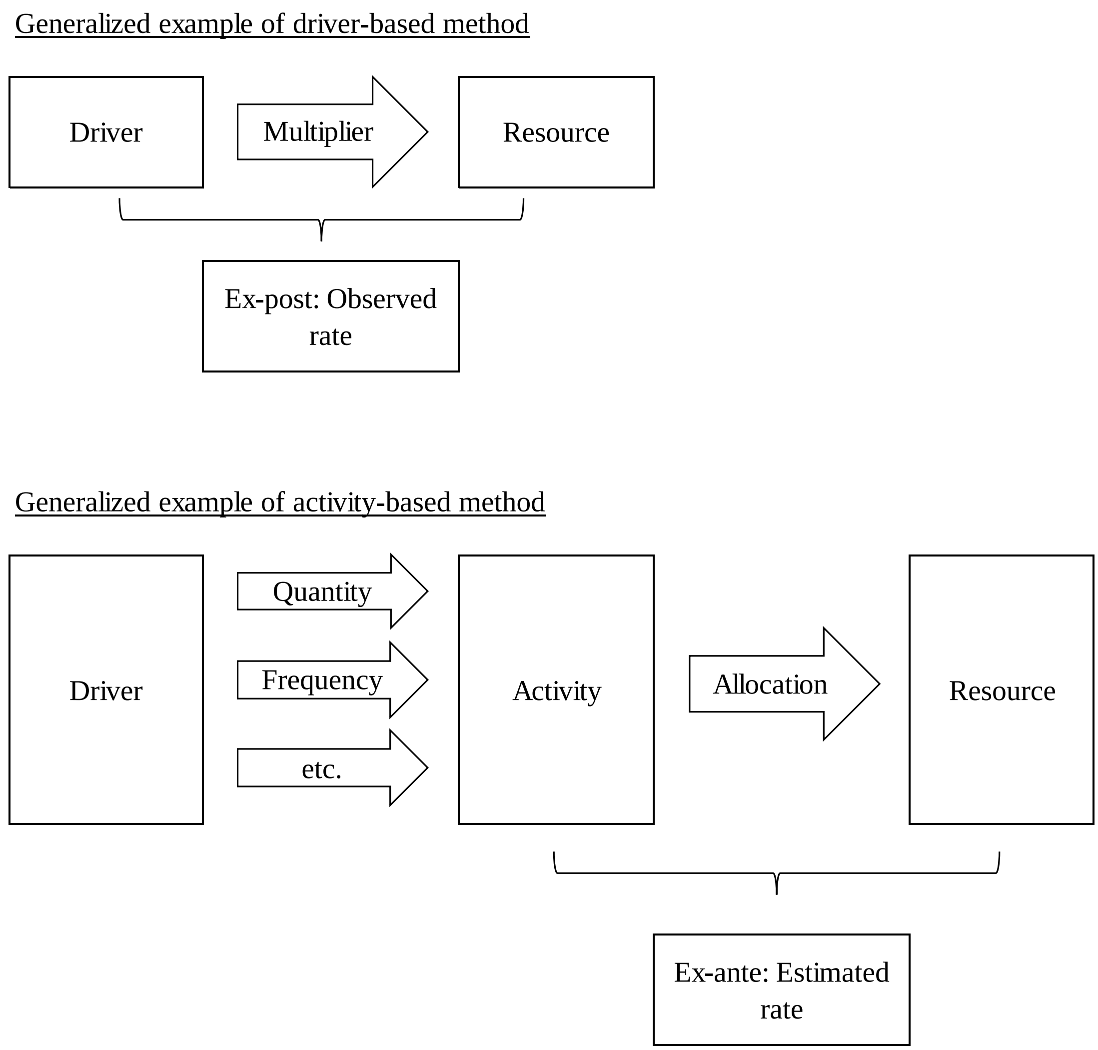

Fig. 1. Generalized examples of driver- and activity-based methods.

In pratice, the activity-based O&SU-rate estimation procedure for our case school building consist of 5 phases: *1. Gathering building-layout data, 2. Gathering planned-activity data for teaching hours, 3. Gathering planned-activity data for non-teaching hours, 4. Allocating activities to spaces, and 5. Iteratively improving on the building layout based on findings.* These steps are further elaborated in section 6 of this paper.

4.2. Drawbacks and benefits of activity-based methods

By using activity-based methods, we can alleviate the aforementioned issues related to using driver-based methods. However, the downside to using activity-based methods is the imminent increase in complexity. As described above, activity-based methods require an additional intermediate step: we must first convert the underlying drivers to a list of corresponding activities. In our school building example, we should first convert the number of students into the required number of teaching hours. The conversion is affected not only by the number of students, but also other factors such as the maximum class size and curriculum hours for each subject. For example the number of activity hours would be different for two schools with the same amount of students, but different maximum class sizes for physics teaching, or unequal curriculum hours of art teaching. The generalized example of an activity-based method is extended to our case school building in Fig. 2.

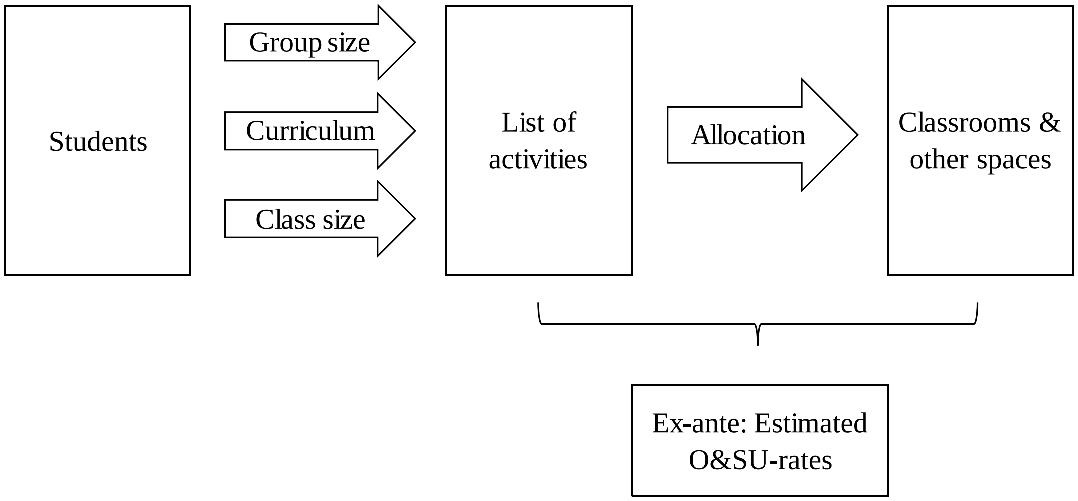

Fig. 2. Example of activity-based method for a school building

Even though the conversion from drivers to activities requires additional work, the benefits of using the activity-based approach are clear. Firstly, this approach allows us to get direct estimates of O&SU-rates, without the need to compare the obtained estimates to benchmarks from previous projects. Additionally, the activity-based approach allows us to easily take into consideration any potential idiosyncratic characteristics of the school, such as an unusually high emphasis on a particular subject.

Furthermore, another benefit of using an activity-based approach relates to the building adaptability and service flexibility of the building. When designing the layout of a building, we should keep in mind not only the currently planned activities of the building, but also how the layout would respond to changes in the activities. By using an activity-based approach, we can estimate both spatial requirements, as well as occupancy rates for different scenarios, which can be used in the flexibility analysis of a building layout. The ability to test alternative activity scenarios is also vital in planning layout-related changes during the renovation of an existing building.

Finally, arguably one of the biggest strengths of using activity-based methods is the fact that the approach can be applied in two distinctive contexts. Firstly, as described by Pennanen [5], activity-based thinking is a novel approach to workspace planning, or in broader terms, the design process of a building layout. Secondly, activity-based thinking can be used to evaluate proposed layouts, regardless of whether they have been designed using an activity-based approach or not. Thus, using activity-based methods allows for an iterative approach to fine-tuning the proposed building layout: the findings from an O&SU-rate estimation procedure can be used as an input in modifying the proposed layout, and the modified layout can then in turn be re-evaluated using the activity-based O&SU-rate estimation, and so on.

In conclusion, the benefits of the activity-based O&SU-rate estimation are not limited to providing estimates of the occupancy rates of a building already before it has been completed or even designed completely, but can also be used as an iterative tool to further improve proposed building layouts.

5. Project introduction

In our case project, we implement the O&SU-rate estimation procedure using planned-activity data for a school building project in the city of Järvenpää, Finland. The building houses both an elementary school, as well as a lower secondary school (grades 0 through 9 combined) with a combined student body of approximately 900 people. The building project's cost budget is 32 million euros and the construction project is completed by August 2019. Morever, the project has particularly ambitious targets as the school aims to be best learning environment in Finland. The estimation procedure is executed with a computational tool developed specifically for activity-based O&SU-rate

estimation, built by the main author of this paper Matti Karjalainen of Boost Brothers Ltd, the company responsible for construction management in the project. While the use of the tool facilitates the O&SU-rate estimation process considerably, it is by no means mandatory in performing the analysis. In fact, the calculations needed for the process are extremely simple. It is only because of the large amount of activity data, and the built-in ability to change the underlying assumptions that make the use of special computational aid relevant.

The end result of the procedure are individual occupancy and space utilization -rates for the spaces in the school building. We only include spaces constituting the Usable Floor Area (UFA) in the analysis, and thus do not estimate the O&SU-rates of mechanical equipment rooms, staircases etc.

6. Occupancy & space utilization -rate estimation procedure

In this section, we describe implementing the planned-activity based approach to evaluating the layout through O&SU-rate estimation in our case project. The approach consists of five phases, which are elaborated in the following paragraphs. Fig. 3 illustrates the activity-based process extended to the estimation procedure.

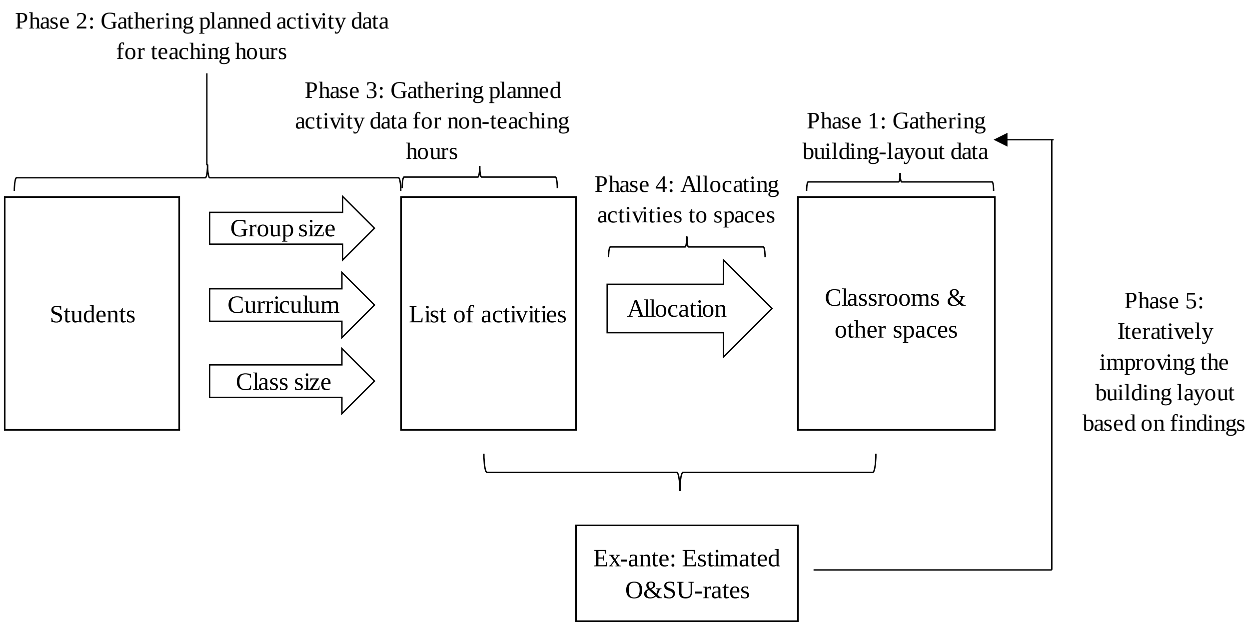

Fig. 3. O&SU-rate estimation procedure

6.1. Gathering building-layout data

We begin by transforming the proposed building layout into a listing of the different types of spaces, along with their areas, student capacity and number of instances. For each type of space, we also define availability during different time periods. Most likely, the typical daily maximum availability for most types of spaces in a school building lies between 10 and 18 hours, but taking a 24-hour availability approach is also possible, and in some cases desired. Moreover, it should be taken into consideration that the availability for different spaces is likely to vary not only between different weekdays, but also between seasons. This issue can be most conveniently tackled by making separate occupancy rate estimations for different seasons, as was done in our example case.

In addition to availability, maximum and target rates of occupancy should be defined. According to Pennanen [5], the degree of predictability of the planned activities in the space should influence our setting of target rates. For instance, occupancy rates of over 50% tend to cause collisions when activities are unpredictable, whereas spaces with more scheduled and predictable activities allow for greater occupancy rates. Previous experience has shown that when the occupancy rate exceeds 80% in schools (activities with mostly high degrees of predictability), a shortage of space tends to occur. The target occupancy rate should thus not be set at 100%, even when the degree of predictability is high. However, we must be careful when setting our target occupancy rates for school buildings with a high number of younger students, as the scheduling of activities is not only bounded by spatial restrictions, but also the schedule-related restrictions of younger students. Thus, we set out initial target occupancy rate rather conservatively at 70%.

6.2. Gathering planned activity data for teaching hours

The second part of the estimation procedure entails composing a list of the activities that are planned to take place in the school building. We begin composing the list by turning to the curriculum. In Finland, the curriculum for elementary and lower secondary school students is very standardized, and well documented. We can thus construct an exhaustive list of planned teaching activities, simply by defining the amount of class-groups in each grade, general class size, as well as teaching class size for each subject. For each subject and each grade, we simply multiply the weekly teaching hours of the subject in the curriculum by the general class size and the number of class-groups for the grade, and then divide this number by the teaching class size for each subject. This gives us the total planned activity hours for the subject for each grade. When repeating this procedure for all classes and all subjects, we get an exhaustive list of the planned teaching activities in the school building.

Then, we add further extracurricular activities such as individual and group studying hours, lunch-time eating, cleaning etc. Determining the amount of such activities requires more judgement, but can be rather easily estimated by generalizing the average amount of daily time spent on each activity at each grade, and using the described multiplication-division procedure. Finally, we estimate the amount of non-teaching activities of the staff (such as grading, breakroom activity, meetings etc.) which can be obtained through interviews with the school staff, if direct data on these activities is not available.

6.3. Gathering planned activity data for non-teaching hours

One should note, that the activities described above only account for the teaching hours of the building. To estimate the total O&SU-rates of the building, we should also consider activities outside of the teaching hours. In Finland, school buildings generally stay open past the teaching hours, to be used by external users such as local sports clubs, orchestras, meetings etc. In our case example, we constructed a list of such activities mostly by interviewing local clubs, and relying on information from similar school buildings in the region. A key finding from constructing such a list (beyond using it to generate O&SU-rate estimates outside of the teaching hours) is that it seems facilitate in communicating to the stakeholder groups of the building, if expectations for O&SU-rates outside of the teaching hours seem to be set at unrealistic levels. While the list of activities is prone to be heavily assumption-dependent, we found that it serves as an efficient way of communicating the mismatch between activity demand, and initial expectations of efficiency.

6.4. Allocating activities to spaces

The next step in our O&SU-rate estimation procedure is to allocate each activity to a corresponding space. We must point out, that many activities should be fully allocated to multiple spaces (such as physical education in both the gym, as well as the locker rooms), even though the students will only be physically present in one space at a time. By allocating activities with given durations, we arrive at an occupancy rate estimate for each space. Simultaneously, since each activity has a user amount, these add up to form an estimate of the space utilization rate.

In our case example, simply the teaching activities consist of 271 distinct activities, allocated initially into 46 distinct spaces. For the initial layout proposal, we arrived at an estimated average occupancy rate of approximately 63% during teaching hours, with a space utilization rate of 93%.

Following that, the results of O&SU-rate estimation procedure were carefully reviewed and evaluated by the building project's client and user organizations. In addition, the client and user organizations utilized the results both in investment and project management decision-making.

6.5. Iteratively improving the building layout based on findings

Finally, we take advantage of an activity based approach through iterative improvement of the layout. Based on the findings of our initial O&SU-rate estimation, the proposed layout seemed to be slightly inefficient, falling short of our target occupancy rate of 70%. After a round of iteration, a revised layout proposal was once again evaluated using the described O&SU-rate estimation procedure. This time, the estimated average occupancy rate was 69%, close to our target rate of 70%, with a marginally reduced space utilization rate of 92%. Additionally, at this point, the non-teaching hour occupancy rate was estimated to be approximately 29%.

7. Summary of results and findings from case example

This exploratory study was set to describe a method for estimating the occupancy- and space utilization rates in non-residential buildings using planned-activity -based data. After covering previous studies on O&SU rates, the quantitative procedure for estimating O&SU rates was described in real life case study. The case study was a school building project in Southern Finland aimed for 900 students with a budget of 32 million euros.

The planned-activity based approach to evaluating a school building layout through O&SU-rate estimation consists of five phases: *1. Gathering building-layout data, 2. Gathering planned-activity data for teaching hours, 3. Gathering planned-activity data for non-teaching hours, 4. Allocating activities to spaces, and 5. Iteratively improving on the building layout based on findings.*

As described above, performing an identical O&SU-rate estimation procedure for the initial layout, as well as the second iteration allowed us to not only compare the efficiency of the layouts, but also get a tangible, numerical estimate of the magnitude of the changes to the occupancy and space utilization rates. Moreover, this enabled to improve building layout design and decision-making process in the project. Obtaining such estimates using a direct driver-based approach would have been extremely difficult, if not impossible.

Based on the observations from the case study we find that the ability to obtain estimates of O&SU-rates during the design process of a building seems to provide value to multiple stakeholder groups. Firstly, for tenants, the risk of a building with problematically high occupancy and space utilization rates is alleviated, improving tenant satisfaction. For building operators, an estimate of O&SU-rates helps in optimizing the maintenance schedules and budgets, as well as the HVAC-systems of the building. For building owners, the O&SU-rate estimates help with managing the project scope, and setting realistic expectations for possible rental income cash flows.

Moreover, in our case example, introducing the O&SU-rate estimation procedure during the design process received positive feedback from the client. While the procedure provides only tentative estimates of O&SU-rates, the clients's management felt that it serves as a handy tool when evaluating the scope of the project. However, as the concept of using planned-activity data in O&SU-rate estimation is new and not widely in use, we observed that it is extremely important to thoroughly introduce the methodology behind the obtained estimates when communicating them to the client and other relevant stakeholders. Once the client and other stakeholders fully understand the methodology of the procedure, an objective re-evaluation of the building layout and scope in collaboration between the stakeholder groups becomes possible.

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Evaluating Performance of TQM Management in Mechanical Construction in the UAE

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Abstract

Construction productivity has been a recurring problem throughout international construction. Stagnant productivity increases project costs and bid prices, jeopardizes completion dates, and adversely impacts safety and quality during project delivery. Reduced productivity can result from a variety of labour, management and sector/process factors. Management techniques can be argued to have the greatest potential for productivity increase and thus the focus of this study. Specifically, research was undertaken to explore the effectiveness of using Total Quality Management (TQM) in a middle-eastern context. TQM approaches have been proven to provide positive impact and to increase productivity in both controlled manufacturing and in construction activities. Nevertheless, the approach has been seldomly used in the (United Arab Emirates) UAE or the broader Middle East. Past efforts have demonstrated the effectiveness of TQM-based approaches on electrical subcontracts for commercial development and, using a similar approach, results are expanded to evaluate mechanical activities. On-going performance of teams completing like activities under a common schedule were evaluated and earned value data collected to compare the impact of active management to status-quo approaches, which are traditionally top-down and authoritarian in nature. Results are presented and compared to performance of electrical subcontracting activities to identify broader conclusions based on the research results. Future research efforts are outlined.

Keywords: case studies; construction management; productivity; total quality management; TQM

1. Main text

Construction is a vital indicator of economic growth for countries around the world. This is particularly true for growing economies such as those in the rapidly expanding Gulf Cooperation Council (GCC) states, such as the United Arab Emirates (UAE). In these nations, ambition is on full display and construction activities continue to commence at a fervent pace building towards the Expo 2020 opening and beyond. The industry continues to be a significant economic driver as a multi-billion dollar sector contributing more than 20% of the national GDP. Together with tourism and finance, the UAE in general and Dubai in particular are on the map as one of the premier international tourist

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destinations. The city has, through its ambitious development, become a destination of prominence not only for tourism but for business and commerce.

The industry, historically, has "been buoyed by the oil economy, high liquidity, a stable political environment and the availability of cheap labor from surrounding Asian and African countries. … Construction project sites are typically a melting pot of dozens of nationalities, which brings about challenges in terms of language barriers and customs, cultural norms with respect to work initiative and views of authority, work ethics, and so on." [1] With strong drive directed, in general, by Arab culture ambition with a diverse central to east Asian workforce, authoritarian forms of leadership have become the norm with little consideration of input from labor. Leadership focuses on getting the job done expeditiously as opposed to collaboratively.

Studies performed throughout the literature and often based on western data have demonstrated that labor may account for upwards of 40% of the direct capital costs on projects overall and upwards of 50% on electrical and mechanical subcontracts [2]. These percentages have been demonstrated to apply both to Western projects and to international projects where the low cost of labor is countered by volume of skilled and unskilled laborers and reduced labor productivity per person [2]. This may challenge the prevailing or conventional wisdom that output in Middle East markets is not affected by labor due to the low wages. With such percentages, significant savings may result in terms of time and in terms of money by employing techniques to increase productivity in a Middle East context.

Inefficiencies which lead to reduced productivity result from labor, management and industrial/sector factors. Considering these three factors, there is limited benefit which can be realized by making the workers, 'work-harder'. Energy is limited and it does not do any good unless working harder is also coupled with working smarter. Management decisions are often directly tied to the ability of the work force to increase productive work time as opposed to expending effort on supporting tasks or non-productive tasks. While it is true that ergonomics and other factors can help workers develop increased performance, it is the focus of this study to address working smarter through management intervention and changes which have the potential for significant impact on job-site.

One proven approach to impact job-site performance is to alter the management style and there are many viable alternatives which have been shown to have benefit. One such approach is total quality management (TQM) which has been demonstrated to measurably improve performance in manufacturing globally and on construction projects nationally. Studies performed on construction projects have been shown to have some effect but despite the promise for positive impact, TQM adoption in the construction industry is sporadic when examining the international marketplace. In the Gulf-states, TQM is seldom used on construction projects, perhaps due to cultural perception or time/project delivery urgency. Given the potential of the approach, implementation on UAE construction sites is nevertheless attractive and it is theorized that, with the right leadership and deliberate implementation, significant impact could be made throughout the Middle East.

An opportunity existed to explore the impact of applying TQM principles on an actual project undertaken in the Emirate of Dubai for electrical subcontracting. The project utilized for this examination was symmetric around the centerline of development. To explore the concept, electrical subcontracting tasks were compared and contrasted using status-quo versus TQM approaches and results were published comparing mirror-image activities with TQM management versus status-quo authoritarian management [1]. This study extends the evaluation by using the same site to examine mechanical construction activities. As with the electrical study, one side of the project was constructed and managed using typical management procedures, which were generally top-down and authoritarian in nature. The other side of the project, contained all the same tasks but was constructed and managed incorporating TQM principles. The project will be described as will the alternative management approaches employed in the following sections. To measure the performance and to evaluate the differences between the respective teams or sides, earned value analysis data was collected and evaluated. The differences between the two approaches are shown to explore whether superiority of the TQM approach is justified by the results, either empirically or quantitatively.

2. Background Literature

The study undertaken seeks to prove the importance and benefit of employing TQM principles for mechanical subcontracting using a case study from the Emirate of Dubai and builds upon research previously published for electrical subcontracting. Employing TQM principles is intended to provide positive benefit in terms of productivity, which leads to positive impacts in cost control, time, quality and safety. The productivity 'crisis' has emerged due to stagnant or negative growth of the industry internationally, including in the GCC countries of the Middle East [2] and factors which affect the industry have been known, investigated and discussed for some time. [3,4,5,6]. These factors can generally be attributed to labor effects and labor effort or lack of effort, management practices and management decision making, and instantiated inefficiencies within the industry, such as within codes and regulations. Studies have shown that limited benefit can be obtained by trying to coerce additional effort as workers are generally limited in terms of energy. Some benefits can be obtained through ergonomics but large benefits can be achieved by addressing management decisions which lead to non-productive effort or excessive supporting efforts. The management philosophy, such as the implementation of TQM, is one such factor that can be explored.

Total quality management (TQM) has been employed in manufacturing since the late 1970's / early 1980's. The approach focuses on customer satisfaction and involvement of all parties in improvement of the processes and subsequent products. With TQM, manufacturing processes have been revitalized while also changing the environment and culture surrounding work tasks. Combining these impacts gives the following guiding principles for TQM, as per the American Society of Quality: customer focus, total employee involvement, processed centered thinking, system integration, strategic and systematic approaches, continual process improvement, fact-based decision making, and communications. [7]

TQM has been shown to benefit a myriad of industries and construction is no exception. Despite the potential, there is little research supporting the benefits in mechanical, electrical and plumbing activities on construction sites. When applying the approach to a specific cultural context, such as the Middle East, research results and activities are even more scarce. This research activity and study seeks to add to the body of knowledge and to provide supporting information for more widespread application of TQM in the Gulf states. Research that does provide compelling evidence of effectiveness of the approach, while limited, is compelling. For instance, work done through sponsorship of the Construction Industry Institute (CII) found strong correlations between management practices and overall project performance with a 40% improvement of labor productivity in mechanical trades. [8] Higher gains were seen in pre-project planning tasks which further benefit the overall project delivery.

Surveys were implemented specifically in Dubai during the height of the construction boom in 2007 to identify factors which were deemed to be important for success of implementing TQM in construction. [9]. Barriers to implementation were also identified. While this work was qualitative and not statistically rigorous, it did show that top management commitment and customer satisfaction were critical to successful implementation of TQM. Other work performed in the region similarly showed best practices and critical success factors in Iran [5] and Egypt [10].

3. The Opportunity for Comparison of Approaches

As previously mentioned, an opportunity to study the effectiveness of TQM processes presented itself during an electrical subcontract on a large, multi-use development in the Emirates of Dubai. A paper was written on this subject and previously published [1]. This same project, with the mirror-image activities, also permitted further exploration of the impact of management approaches on mechanical rough-in subcontract. The project is part of a large multi-use development with numerous commercial spaces for retail, parking, leisure and entertainment together with supporting infrastructure. In total, the overall project consisted of over a million square feet of development in a mirror-image arrangement as shown in Figure 1, which shows the symmetry but not the details of the project. The mechanical subcontract required rough-in of ducts with and without insulation, drainage pipes, CPVC cold water plumbing, and wet-pipe sprinkler systems. All mechanical elements were rough-ins and no fixtures were included in the subcontract. All required elements were identical for these elements on either side of the project with 74 identical units on mirrored on the centerline. The two sides of the project were divided into separate autonomous teams. Each team had its own skilled and unskilled labor, foremen and superintendents. The leadership on each side of the project reported directly to the project manager whom facilitated the study and collected data on the project as it was being performed. Crew sizes, equipment and support staff were, as much as possible, identical on both sides in terms of quantity and capabilities to minimize and eliminate bias as much as possible. Each team used the same inventory/storage facility, the same administrative staff/time-keepers and safety personnel. Independent quantity surveyors were engaged to confirm quantities installed and ensure the validity of the progress reports submitted.

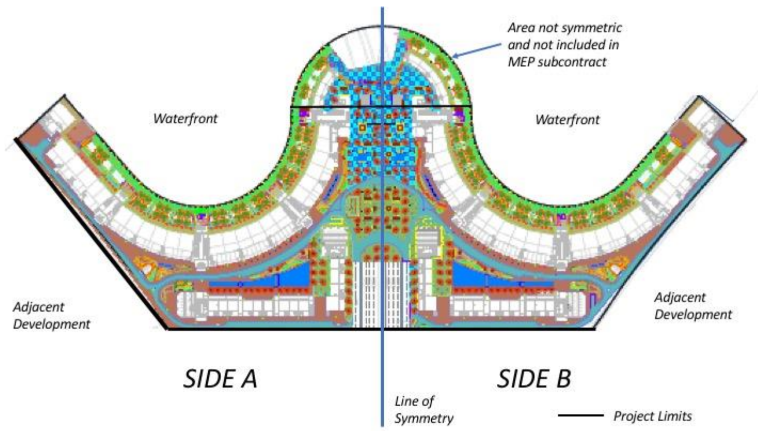

Figure 1: Project Plan Used for Research. [1]

Management using TQM principles were employed on Side A while traditional management approaches were employed on Side B. In the TQM approach, efforts were taken to develop a participatory management style, which laborers were unfamiliar with. This involved significant communication with all participants, skilled and unskilled, management and labor alike. A project quality steering committee was formed including project management representation, quality control engineers, quantity surveyors, project engineers, foremen and superintendents, charge-hands and labor representatives. The project quality steering committee met frequently with the goal of empowering the workforce and facilitating continuous process improvement. For the traditional side, a status-quo approach was taken and a typical authoritarian management style was used. With this style, there are orders that are conveyed from top to bottom with no opportunity for worker feedback. This is in stark contrast to TQM with involvement of all participants. For each side, progress was monitored over the entire period of performance. Quantities installed were recorded on a week-by-week basis as were actual labor hours which provided the basis for earned value management.

Each side had identical plans and schedules, identical activities, and the same availability for materials and any necessary equipment. As mentioned, the work force was identical in terms of composition and competency to minimize bias. The project manager was also careful to ensure that he was not giving undue personal attention to one side versus the other, which may have skewed the results. Although the management focus on the two respective sides greatly differed, the assigned project management support staff on the two sides had equal access and equal time with the project manager.

4. Data Collected

As mentioned, the project involved a set of mechanical rough-in for the facilities. There was no finish work and no installation of large mechanical systems, such as chillers or water treatment facilities. The work performed focused on installation of ductwork and ductwork insulation, the installation of cold water piping and drainage pipe, and fire suppression wet-pipes. The items and the estimated quantities and projected man hours are shown in Table 1. Each side has 259,402 cumulative man-hours budgeted for completion. HVAC installation and Fire suppression are both planned for nearly 100,000 manhours with 65,000 required for plumbing.

The quantity for each item was measured and recorded weekly as were the actual and earned man-hours, the difference of which could indicate cost over or under-runs. Differences in progress, however measured, gives an indication of differences in productivity between the two respective sides as does the ratio of actual and earned manhours.

Table 1. Activities, Quantities and Planned Labor Hours for Lighting and Power on Side A and Side B

Elements	Estimated Quantities	Planned Manhours
HVAC		
GI Duct	49,712	27,618
Black Steel Duct	32,433	18,018
Duct Insulation - Inside	1,148	25,000
Duct Insulation - Exhaust	5,861	23,444
Support Systems for Duct work	11,229	3,238
Total HVAC		*97,318*
PLUMBING		
Drainage Pipes - Above Grade (UPVC)	12,002	26,662
Cold water CPVC Pipes	7,883	6,532
Cold water CPVC Fittings	8,780	21,413
Hangers & Supports for drainage and water supply	6,400	10,140
Total Plumbing (Pipes, Hangers & Supports)		*64,747*
FIRE SUPPRESSION		
Fire suppression wet-pipe (25 to 80 mm)	2,675	24,398
Fire suppression wet-pipe (100 to 200 mm)	26,808	72,939
Total Fire Suppression	*29,483*	*97,337*
Total Man Hours - Project		259,402

5. Analysis and Results

For the HVAC and the plumbing systems, hangers and supports are required to be installed prior to the supporting ducts and piping. Both of these items were complete on both sides of the project before the schedule completion date at week 19. In terms of the HVAC supporting hardware, both sides were approximately on-target in terms of quantities. For the plumbing support equipment, Side A using TQM exceeded the quantities by 7% while Side be exceeded the expected quantities by 6%, which for all practical purposes is effectively equivalent. The progression of installation in terms of quantities is for HVAC and Plumbing supports are shown in Figure 2.

In terms of costs, the installation of supporting hardware exceeded the estimated costs for both the HVAC system and the Plumbing systems. One major reason for this is the disparity between assumed productivity valued in estimation and planning and the actual values experienced in the field. Considering the HVAC system, the quantities estimated and expected were fairly close to the actual values installed. Yet, in terms of man-hours, there was a 5% increase with the TQM approach and a 30% increase with the traditional approach. For the plumbing supports, quantities were increased due to field decisions on where to place the hardware. Increases were 7% for the TQM approach and 6% for the traditional approach. Actual man-hours were 23% and 34% higher than estimated for Side A and Side B respectively. This is alarming and jeopardizes the profitability of the activities due to unrealistic planning input values. This can be corrected through better data collection and the use of BIM models to ensure and control wastes.

While costs were seen to escalate on both sides of the project, time impacts are more clear and more convincing for supporting systems. Evaluating Figure 2 reveals that in both cases, the Support hardware, for all practical purposes, was effectively complete by week 8, less than 50% of the way into the project. With the traditional management approach, supporting systems were still being implemented during weeks 18 and 19 and possibly delayed other items.

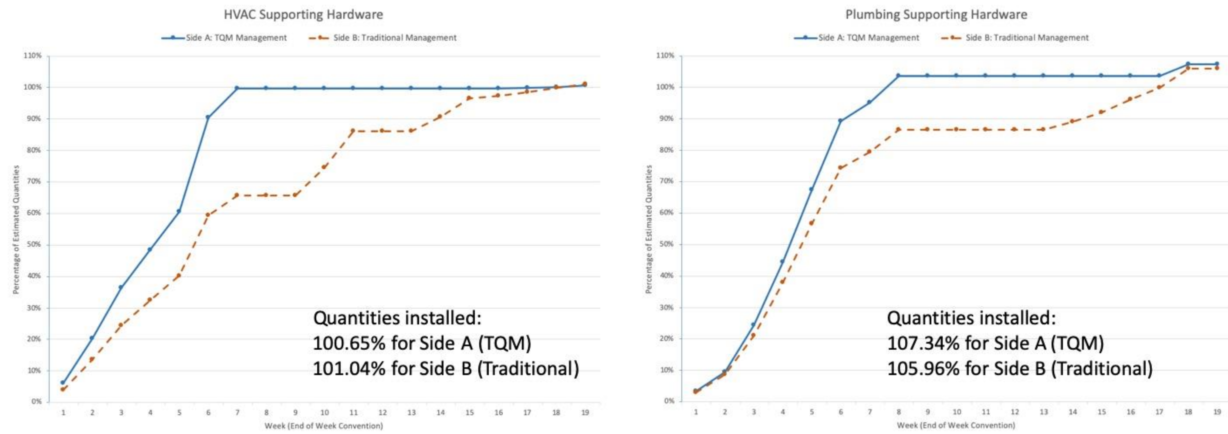

Figure 2: Progress of Supporting Hardware Installation for HVAC and Plumbing

Considering HVAC and Plumbing activities as a whole, the crews working on Side A with the TQM approach were able to complete the rough-ins by the 19-week deadline. For Side B, work was not completed within the required timeframe and delays were experienced. These delays can only be attributed to the management style and provide convincing empirical evidence of the impact of a TQM approach in the Middle East. Considering quantities, 89% of the estimated quantity of HVAC components were installed by the 19 week planned completion. These activities were not complete at week 19. For plumbing activities, actual installed values at completion on Side A were 109.1% corresponding to a 10% increase in plumbing materials. At week 19, Side B was not complete but was at 102% of estimated quantities. It is expected that the quantities installed would meet or exceed the quantities installed by the TQM focused crews.

The progress of the HVAC and Plumbing activities collectively can be sown in Figure 3. It may be seen that the productivities of the activities are comparable during the first two weeks of work for both sides of the project. However, the productivity steadily decreases over time on under traditional management approaches when compared to the equivalent activities being performed on Side A. Costs for both the ductwork and for the plumbing exceeded the estimates by 13% to 25% for HVAC, depending on the specific detail and 20% to 35% on plumbing. Overall costs were approximately 3% higher using the TQM approach for HVAC rough-ins. The opposite was true on plumbing where cost for the TQM approach was approximately 4% lower than traditional management costs. In both cases the cost escalation was an area of concern and can be attributed to higher than expected wastes and inefficient use of materials together with material price increases that were not properly accounted for.

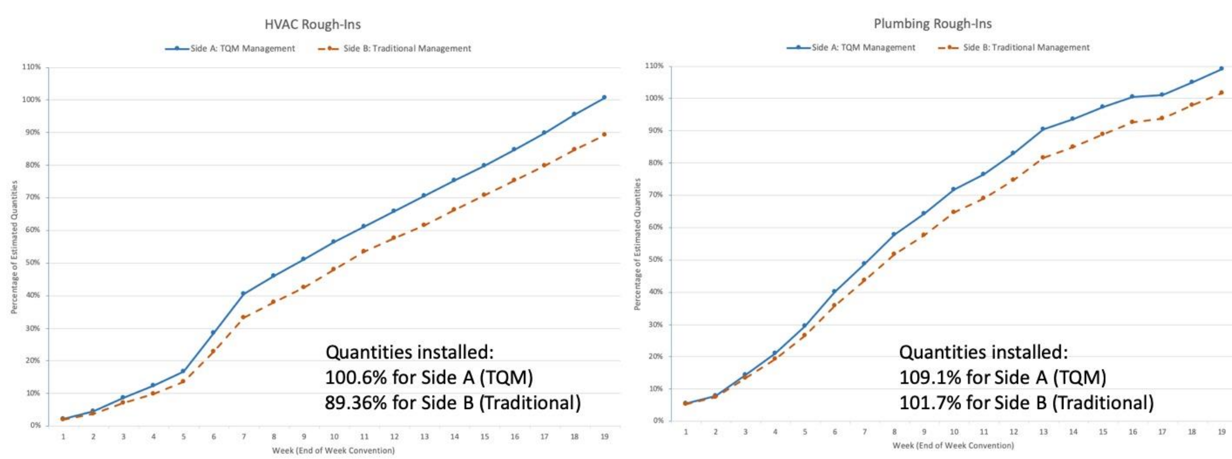

Figure 3: Progress of HVAC and Plumbing Activities Throughout Project

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It is difficult to make a conclusion of the superiority of one approach versus another with respect to costs. However, it is clear when examining Figure 3 that the TQM approach has a clear impact on the time for project completion. This is compelling information that could encourage more widespread use of TQM in the Middle East.

The contract required the installation of fire suppression wet-pipe and values were aggregated into small (800 mm and below) versus large (100 mm or above) diameter pipe. Overall, values between the two sides in terms of quantities tracked very closely between the two sides as may be seen in Figure 4. This is a curious result as one would expect that the TQM approach would show a similar trend to the observed data for HVAC and Plumbing. It is unknown why a clear difference between the two approaches was not observed and more information and additional research must be performed to identify the causes. It is possible that material availability limitations with large diameter wet-pipe, which was still not complete at week 19, constrained the installation of smaller diameter pipes. Costs of the fire suppression activities were significantly above estimates nearly doubling on both sides of the project. The costs on the TQM side were clearly superior and were 10% less than the equivalent costs on Side B with traditional management. It is uncertain as to why the difference occurred given the similar timeframe of materials installation. This would infer that there is less efficiency of the crews with traditional management styles but more information must be collected to validate that hypothesis. The fire suppression system was incomplete on both sides of the project at the conclusion of week 19.

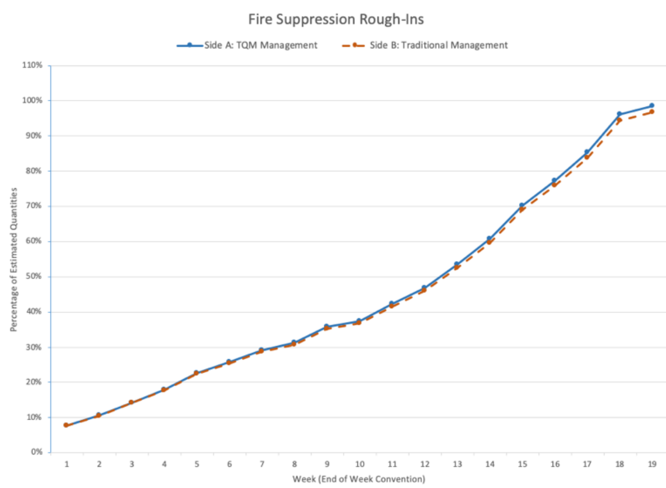

Figure 4: Progress of the Installation of Fire Suppression Wet-Pipe on Side A versus Side B.

The quantities installed as well as the manhours expended can give an estimate of the differences in productivities between the two sides. Looking at quantities, there is approximately a 14% increase in productivity that was observed for HVAC duct installation and associated insulation. For plumbing pipe installation and fixtures, an increase of 8% was observed by applying the TQM approach as calculated using quantities. The difference in fire suppression wet-pipe was nominal with a calculated increase of 1.5% observed by using TQM.

6. Summary and Conclusions

This research effort capitalized upon the unique opportunity presented by a mirror-image project in the Middle East. With the forward-thinking of the subcontractor and project manager, a research student was introduced for a small subcontract with mechanical rough-ins. This paralleled and built upon the successful results found through electrical subcontracting on the same project [1]. The project was structured where one-half of the project was delivered using a TQM approach while the mirror image was completed using status-quo authoritarian approaches. The data collected showed quantities installed together with manhours expended and earned value. The data was evaluated to make conclusions based on the results. It was shown for the HVAC installation, Plumbing installation and associated HVAC/Plumbing supporting elements, that there was a clear difference in the performance between the TQM and status quo approaches. Significant productivity gains were realized. Costs on both sides escalated; however, this was due to insufficient or overly optimistic estimates or unexpected material price escalation. With the mirror image projects started at the same time, the TQM approach clearly finished within the time-frame in cases where work was delayed under the traditional management approach. The one exception is the installation of fire-suppression wet-pipe, which was delayed on both sides of the project.

7. Acknowledgements

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Examination of advanced fastening systems for the use of robots in the construction industry

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Abstract

Since robotics become more widespread in the construction industry, more construction phases and work steps must be covered with one robot system. Current robot systems are used almost exclusively in precast construction. At the construction site, so far only prototypes are in use, and only individual parts of the building shell construction and assembly can be covered. This paper examines to what extent fastenings are necessary to increase the operating range of robots and which boundary conditions exist or need to be addressed. Automated construction, and more precisely installation of fastenings, has so far been partially implemented, which has shown increased productivity as well as installation quality, thus load-bearing safety. This knowledge must now be extended to robots. The present work is based on an overview of current research and development and on the current research on a cable robot for brickwork construction at the university Duisburg-Essen. It further demonstrates that fastenings pose an important further application, especially in order to explore the extended phases towards the brickwork or contour crafting. It can be assumed that robots will become increasingly important in the construction industry. Reasons include high quality, safety, speed and economic aspects.

Keywords: Advanced fastening systems; Fixings and fastenings; Robots in the construction industry; Automatisation/Automation

1. Introduction

Robot systems in the construction industry have been researched since the early 1980s. Since then, the use of robots has first been established in factories for precast structural elements. These systems are used here, as in other areas of stationary production as well, for many consistent tasks. Contrary to this, robot systems have not been able to assert on the construction site to this day as discussed in previous publications [1], [2], [3]. A possible reason for this is the reliance of the construction industry on 2D model prints, as well as unique project/product specifications, which limits

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the mobility programming of robots. Another reason is the limited working envelope of machines, i.e. lack of free movement systems for a robot along a wide part of the construction site.

However, these constraints seem to experience a period of transformation in the last years, while assembly of construction elements may be largely facilitated [4], [5]. This paper describes the requirements and possible methods in the construction industry as regards the installation of fixings and assembly of fitted elements by robots. On this basis, the further research and applicability potential and necessity are inquired, and directions for further investigations are established. In the following, the importance of fixations in the described area of application is introduced. Then, some construction tasks and objectives with regards to fastenings are presented, with emphasis on those which a robot system can perform better than humans under specific conditions. Also, other reasons for considering the implementation of robots for these tasks are discussed, such as e.g. health and safety at work, quality, or avoidance of defects due to human errors.

2. Presentation of robot systems in the building industry

Before going on to fixations, a brief outline of robotics in the construction industry is given. This is necessary to understand the open questions.

In the 80's of the previous century for the first time the topic of the automated construction of buildings was discussed in a larger circle. At that time, the portal robot has been considered to be particularly suitable for the construction of buildings. Until today, these types of robots are often used, because they can bridge high spans. Today many of the earlier 2000 robot systems can be found in precast factories. Robot systems, which can be installed directly on the construction site, were not followed up during the conception phase. Some concepts considered an automated approach where the fixations are inserted from above and the covered with concrete. However, many do not address this topic at all, or these activities are finally still manually carried out. Examples are the construction robots in Japan, where the reinforcement is interlaced manually. These activities will also continue to be performed manually for the systems presented in Table 1.

Table 1: Systems, basic platforms and manufacturing processes for (partially) autonomous building construction

Name	Basis platform	manufacturing method
Apis Cor	Modified robot arm	Contour Crafting
Hadrian	Modified crawler excavator	brickwork
Hadrian X	Modified truck with cantilever arm	brickwork
SAM	Robot arm	brickwork
Wirerobot for contruction	Wire robot	brickwork
Spiderbot	Wire robot	Contour Crafting
Kamermaker	Portal robot	Contour Crafting
Vulcan + Vulcan II	Portal robot	Contour Crafting

From a construction point of view, the manufacturing processes are particularly interesting. The above shown systems can only be used to a limited extend of the building shell construction. Thus, the actual systems are limited to parts of the building shell and cannot be used to other construction methods. As a result, many of the extended construction activities like the insertion of windows or setting the roof truss cannot currently be automated using these systems.

When robot systems are to be used in the extended bodyshell and set fixings, new challenges arise:

- It is not possible to use the same mechanism for setting fastenings like e.g. building with concrete.

- The usage of several robot types is a cost driver, which currently leads to a point of continuing with an existing robot system, while modular approaches are not applicable.
- It must be decided whether first the fixings and then the component should be set or both at the same time.
- Clarification is needed as to if conventional or not conventional standardized fixing products can be used
- New fixing methods for usage in robot driven systems need to be standardised
- The construction process must remain continuous and undisturbed

3. Parameters that determine the use of fixtures by robot systems in the construction industry

In addition to the challenges just described, there are further parameters affecting the usage of robot systems. The following list gives an overview:

Heaviness: The high weight of robot systems makes it difficult to use them on site. For installation, the subfloor must be sufficiently load-bearing, installation on floor slabs is made more difficult or is not possible, and adequate stability must be demonstrated.

Speed: The speed of the overall system for moving components has a direct influence on the overall construction time. This includes the procedure or moving of the base platform, as well as the speed of the end effector.

Complexity: The complexity is conditioned by properties such as: Operation, construction, programming and the pre-processing.

Payload: A low payload means the displacement of smaller components and a shorter construction time. Some components require a minimum payload.

Radius of action: A small radius of action requires frequent repositioning of the robot system. Moving the entire system is at the expense of the construction speed.

Height limitation: The systems should be able to erect several storeys without having to dismantle and erect them at great expense.

Sensitivity to environmental influences: In order to be used on the construction site, sufficient insensitivity to environmental influences should be ensured. The systems should be insensitive to dust, heat, cold and water. Mechanical shocks are to be expected.

Costs of use: The operational costs of the overall system have a direct influence on the economic efficiency and the operational hurdle for companies.

In addition, simulations have shown that the usage of robots only in shell construction is not economically efficient. The systems must be used in further construction phases. In these phases the setting of fixtures becomes of essential importance. Work in the extended shell construction phase can include various fittings, such as the installation of facade elements, balconies, windows, door frames, HVAC parts, or receptors for building expansion. For these installations, advanced fastening systems potentially with adaptable or generic assembly features are important, and robots can be used more efficiently, the more work breakdown structure (WBS) elements they can be involved with. In the following, current conventional fixing types are described.

A large variety of construction products (post-installed or cast-in-place fasteners) together with adaptably designed fixtures for various building configurations and uses represent modern fastening technology. Furthermore, a consistent set of product performance documents [6] and structural design calculation standards [7] form the basis for specifying, detailing, and installing fastenings. The large variety of products in the market (see an exemplary presentation in Fig. 1) aims to satisfy a variety of performance requirements with considerations on minimising costs and assembly speeds. These requirements include available dimensional configurations, load-bearing capacities, and wider project specifications such as thermal and noise insulation, fire resistance, durability, environmental footprint, aesthetics, and ease of removal. Post-installed anchors are mostly available for use in concrete and masonry, while some applications of post-installed anchors for steel structures, wood, and other construction materials are also available in the market. Although each anchor has individual installation procedures, the generic steps for anchor installation can be described as follows:

- Marking of fastening point
- Drilling of borehole (perpendicularly and using the appropriate drilling tools)
- Cleaning of borehole (removal of drill dust)
- Preparation/mixing of injection mortar (for bonded anchors)
- Insertion of anchor at appropriate depth
- Tightening of nut to the correct torque
- Optionally: load-testing of anchor

Furthermore, mostly depending on the nature of the fixture, and the construction plan, two different types of fixture assembly can be used as seen in Fig. 2. The assembly with pre-positioned anchors requires that all the above steps up to anchor installation occur prior to placing and securing the fixture. This requires that the drilled hole in the base material is larger than the clearance hole in the fastened element. Simultaneously, this requires a very precise positioning of the anchor in order to avoid clashes with the fixture holes. Post installation configurations use the element to be fastened as a drilling and setting template for the anchors. In this case, the diameter of the hole in the component to be fastened should be larger than or equal to the borehole diameter. In this case, it is also important to provide for a safe temporary support of the fixture during the anchor setting procedure. A practical method – though not always applicable – is mixing the above methods by temporarily supporting the fixture with one pre-positioned anchor and subsequently installing the rest of the anchors. An issue with post-installation is the possible damage of the fixture due to the through-drilling procedures, which compromises the appearance and the durability of the system. According to the authors' best knowledge, post-installation is still a preferred method for most applications in the field.

4. Requirements for advanced fastening systems

Prefabrication, automated erection, and modularisation procedures gain in relevance hand in hand with the increasing implementation of digital construction technologies. Besides the parameters of robotised construction discussed above, the use of automated procedures can generally minimise or eliminate typical health and safety risks related to the installation of fixings. These include hand injuries, among other due to drill torque reaction, hand arm vibrations, inhaling of dust, high noise levels, working with chemicals, electric shocks. Robotised construction can also facilitate the installation of fixings where human presence is of unacceptable high health and safety risks or virtually impossible. These cases include installations in very confined spaces, work at height, underwater installations, construction at extreme environmental or space conditions, rehabilitation or decommission of industrial and nuclear facilities.

Besides, it is widely proven that human errors in the installation of fixings can substantially decrease the load bearing capacity of the anchor, occasionally even down to 20% of the expected resistance. Simultaneously, statistics and industry reviews have shown that perhaps the majority of construction professionals are unaware of the exact installation procedures for fixings [8], [9]. A faulty installation can lead to reduced structural safety already at the beginning of the fastenings life-cycle but defects at installation can also propagate to a faster degradation of the fixing and possibly a failure without prior warning [10]. These facts obviously lead to very high technical risks, and this has already led to catastrophic collapses in the past. In order to ensure quality of construction and a permanently high safety level, robotized construction, where human quality control is replaced by automated procedures.

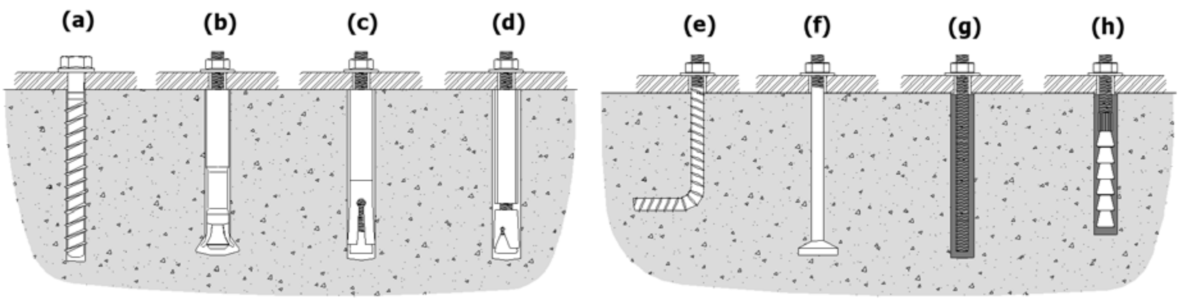

Fig.1. Different anchor types, depending on the installation procedure: (a) concrete screw, (b) undercut anchor, (c) expansion anchor - sleeve type, (d) expansion anchor – bolt type, (e) cast-in-place ribbed and deformed bar, (f) cast-in-place headed stud, (g) bonded anchor with threaded rod, (h) special bonded anchor.

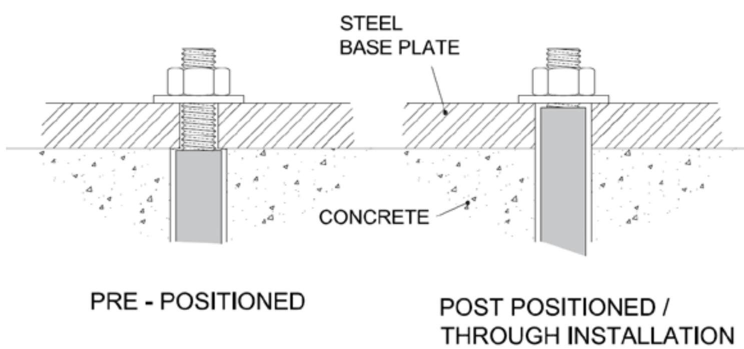

Fig. 2. Anchor installation configurations, dependent on logistic

It should also be mentioned that current design codes propose an additional design safety factor for fixings to account for the installation quality on the load bearing capacity as discussed in the previous paragraph [11]. This safety factor increases the design demand by 40% for less than normal installation safety (e.g. untrained or inexperienced personnel). This also shows a directly proportional increase as regards all aspects of fixings installation such as procurement cost, time, and material resources.

As regards positioning of the anchor, an often-recurring problem is drilling onto or through rebar in concrete. In this case, both the function of the anchor and the efficiency of the reinforcement can be compromised, and as such the borehole is cancelled and a new one must be drilled, at a minimum distance of a few centimetres. This means that the fixing point must also be redesigned. In some cases, this is also due to over- or under-drilling. In order to avoid this effect, the as built drawings, and a ferromagnetic rebar scanner are employed. Tolerances also play a very important role in fastening technology, as they can be decisive for the success of the assembly. Furthermore, tolerances can strongly influence the distribution of loads from the fixture to the individual anchors, e.g. in a group, and consequently lead to excessive load on a single anchor [12]. In absence of redundancy measures, failure of a single anchor can then even lead to collapse of the entire fixture.

The requirements for the fixing system used for an automated assembly are derived from the above descriptions. In summary, specific rules and methods need to be set as regards the interfaces and integration of fastening products with existing robot systems. Also, the generic steps for anchor installation must be reproducible, and insensitive to the location, or variabilities as regards the base material, fixture, or intended use. The fixing product should comply with existing standards, while it should be noted that these standards (typically the certified manufacturer's declaration of performance) dictate the construction/installation method. Finally, it should obviously provide the logistical benefits in order to not negatively affect the speed and construction sequence of the system.

An ideal application would allow the robot system to immediately integrate the complete fastened system (i.e. fixing and fixed component) into the building. This requires a fixation method that accommodates this from a load-bearing and a logistic viewpoint. If the fixing installation is nonetheless performed manually, a robot system should be able to control whether they have been made correctly, e.g. by on site testing and evaluation.

5. Conclusion

This study addresses the use of robots in construction. It departs from extended phases of brickwork or contour crafting, toward the potential and efficiency that can be achieved when robotic installations are developed for fastenings and assemblies of fitted components in construction. This further potential of robotized construction applications is discussed on the basis of particularities and benefits of robotic construction, current obstacles and risks in manual fastening installations, and how these two aspect of construction can be integrated toward a safe and efficient practice.

Based on this exercise, the efficiency of automated fastening assemblies is discerned, while significant new research questions arise. These questions also pose the challenges for research investigations and development of efficient technologies. As regards first applications of robotic systems, the University of Duisburg-Essen is currently developing a cable robot and performs investigations for brickwork construction [13]. The involved scientific teams envisages using this robot system to address the particularities of fastening applications for specific building systems, with appropriate adjustments and extensions of the present system. In order to provide suitable systems to this end, further research is necessary, along the axes of the open questions briefly listed below:

- Which robot types and end effector types are potentially usable for the installation of fastenings and fitted components?
- In which construction phases can automated fixation solutions be used?
- Why current robot systems do not set fixations in the construction industry?
- How do other industries install automated fastenings?
- Which design and construction standards are involved and how should these be adapted?

Once these research questions are addressed, a knowledge basis will become available in order to translate the integrated automated fastening assembly into a real construction system.

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Factors Influencing Construction Time Delay on High Rise Projects In India

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Abstract

In Construction Project delay can be defined as the time over-run from the agreed upon a time which can be written & signed in the form of contract or verbal mutual agreement. Construction Projects often face delays and uses unnecessary time due to various factors and reasons, and hence suffer from unfavourable consequences. This study will identify the significant delay factors from an intensive literature review, supplemented by delay factors in major Indian construction projects based on empirical data. A total of eight ongoing construction projects were selected for the study. And a questionnaire is also used to collect reasons for the delay, their frequency, importance, and severity. 53 valid responses received from the project managers. SPSS 21 tool package is used for statistical analysis and the tests performed were Severity index and the correlation between the attributes. The findings of the study concluded that the maximum severity for delaying projects is due to Design Variation followed by Lack of Proper Planning, and Shortages of Skilled Labour.

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Keywords: Delay; Projects; Construction Management; India.

1. Introduction

Construction Industry is a huge industry which is the most important in creating jobs when it comes to India. However, most of the times it has seen the downturn because of many internal as well as external reasons. Never the less the most important of them is the time delay and cost overrun which hampers the project success immensely in a sense that the project which was very viable to take in the preliminary stage is giving loses at the time of execution. In fact, this is the most important reason why many of the projects are left incomplete and developers move on to the next project [1]–[3]. However, with RERA act came into existence now the developers can't just be left the project without completing it and moving on to the next project, So this is very important to understand the effect as well as factors affecting the Time delays & cost over-run. This thesis is done mainly for the Time delay factors which has identified and ranked different factors. This result is specific to the Indian Country context however, this result will not be much different for other developing countries as well when it comes to Time delay factors [4]–[6].

In most of the countries in the world, experience and the research has found out or revealed that all the successful projects should be completed within the designated time frame for a project. Therefore, the causes of delays or time overrun is an important aspect which should be studied in detail as it affects the profitability of the project. A lot of

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researchers, in their research or papers, have been able to identify such factors that actually affect the delays in a construction project and this affects the economy as well as organizations health. The time overrun in a construction project is usually a cause link to scope, quality and cost for different tasks or work [2], [7]–[9]. No matter how much we speak about the various studies or research been done in analyzing the various factors affecting the delays for various construction projects in India and around the world, we still need to a deeper understanding on this matter to improve it for achieving better results. Indian economy has very impactful manufacturing and another sector which contribute largely to GDP. But construction is still an untouched area which only contributes approximately 5.5 % (1990's data) of overall GPD growth. However, the Indian Construction industry is now expected to be the backbone of the Indian economy & currently, it contributes about 53 % to the GDP, according to the latest report published by the government [10]–[12].

2. Literature Review

In the Construction industry, there are a lot of variables that derives the project and decide its fate in terms of how successful it has met its intended purpose. The construction Industry is always expected to be a growing one especially when we talk specifically with reference to developing countries [13], [14]. In India there are lot many development projects of more than 100 crores are being carried out different states of the country and thus requires huge funds which is a very scarce resource and is important if the country wants to be among the developed ones from the developing ones, this transfer of status is not easy and requires a lot much constructions to be carried out in the next span of 10 years or so. In order to do such type of construction, India needs to plan thoroughly so that there are no much wastages of resources and the projects meet its the purpose. All the construction work needs to be planned in terms of how the work will be executed, who is responsible for that particular work, outlining the scope and requirements, major deliverables, no. of tenders to be floated for a particular project, no. of parties involved in a project (Kim, 1982).

A project can be defined as an endeavour which is temporary in nature and has a definite timeline to follow. It uses resources such as man, materials, plants and equipment's to be able to complete its intended purpose or scope. One thing we all should keep in mind being a constructional professional is that no matter how best we plan our course of action, it will have some lapses and we all know about Parkinson's Law is if anything that can go wrong in a project then it will eventually so we planned according to it also. For a project to be successful, a project must be completed within the requirement and limits of Scope, Quality, and Time & Cost. Thus, one should especially take care about this 4 things in a project and this is what most researchers research about in order to find a standard solution but has been said that each project is unique and thus all things are dynamic in nature and require updating with each new project [15]–[18].

Table 1

S.No	Reference Number	Attributes
1)	[19], [20],	Inaccurate Material Estimate
2)	[5], [21], [22]	Unexpected Weather Condition
3)	[9], [23], [15], [24], [25]	Shortage of Materials
4)		Shortage of Equipment.
5)	[21][14]	Shortage of Skilled Labour.
6)	[26], [26], [27]	Inaccurate Productivity Rate calculation
7)	[8] , [27]–[29]	Location Constraint of Project.
8)	[30]	Lack of Proper Planning

9)	[3], [31], [32]	Poor Productivity of Labour
10)	[21], [22]	Design Variation
11)	[34]–[36]	Inaccurate Productivity estimation of Equipment

I. Supernova (Sec 125, Noida):- The Project is delayed by about 34 months from its initial schedule baseline. The residential building has more than 5o floors.

II. Panchsheel (Sec 75, Noida):- This Project has 22 floors and is been delayed by 19 months and is expected to have more delay.

III. Xerbia Greens (Hinjewadi, Pune):- The Project has 18 floors and is been delayed for 16 months and is currently under construction.

IV. Xerbia MarketYard (Hinjewadi, Pune):- This has 15 floors and the project mainly consist of studio apartments and is being delayed by 16 months from the schedule.

V. The other projects which were studied in this research are Rohan Albania, Pebbles Urbania, Parande Pune Ville, Jewel of India, and Wave City.

The common elements among all the projects discussed above have been delayed by more than 15 months and are large because of the factors being characterized as the factors influencing Construction delays.

3. Research Methodology

On referring to the past records and trends on Construction Productivity in all the major developing countries, we were able to shortlist some of the factors which were the primary causes in delays of the project (Assaf S. A.-K.-H., 1995). We have selected this 12 factors and conducted the survey in the form of questionnaire which was distributed to most of the high rise residential projects who were already in delays more than 6 months & located in Noida & Pune where the Project In-charge or Project Manager was asked to fill up his responses (Peter F. Kaming, 2010). The Questionnaire mainly asked them to rank these 10 factors according to them in terms of priority and what according to them has most significantly delayed the projects. All the project managers were asked to rank all the factors from 1 to 5 with 5 being the most important factor & 1 being the lowest importance in terms of delay.

3.1. Data collection

The questionnaire floated to about 53 Project Managers who are currently working or has done high rise residential Projects in India. This sample does represent the whole population as it is been already discussed in one of the papers (Kim, 1982). Several of the papers have used this same methodology for their research (Assaf S. A.-K.-H., 1995) (Peter F. Kaming, 2010). Most of them answered over a phone call or through meeting and few handfuls of people have filled in the form floated, Some of them has agreed to reveal their identity in the research paper but the majority of them has asked to be confidential as it has lots of secret information regarding the schedule and budget of the project. One of the Project managers was Nimesh Patel Sir who is working on a project of high rise residential building in Pune as Project Manager from consultant side and name of the organization is GLEEDS INDIA & Similarly, Thirty-two (32) managers mainly construction manager working on a high rise residential projects in India were asked to give response against a set of questions in the form of questionnaire.

Table 2

S.No.	Variables of Delays	Frequency		Importance		Severity	
		Rank	Index	Rank	Index	Rank	Index

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1.	Inaccurate Material Estimate	2	0.76	5	0.62	4	0.48
2.	Unexpected Weather Condition	10	0.45	9	0.52	10	0.23
3.	Shortage of Materials	7	0.52	6	0.61	7	0.32
4.	Shortage of Equipment's	6	0.58	10	0.5	9	0.29
5.	Shortage of Skilled Labour	4	0.61	3	0.8	3	0.49
6.	Inaccurate Productivity Rate calculation	8	0.49	4	0.7	6	0.34
7.	Location Constraint of Project	10	0.24	11	0.4	11	0.1
8.	Lack of Proper Planning.	3	0.62	2	0.82	2	0.51
9.	Poor Productivity of Labour	5	0.59	7	0.6	5	0.36
10.	Design Variation	1	0.9	1	1.0	1	0.9
11.	Inaccurate Productivity estimation of Equipment	9	0.50	8	0.59	8	0.30

4. Result and Discussion

Table 3, shows the various factors according to importance index & frequency index and from which the severity index is calculated and noted down. Severity index of various factors is the product of Importance index and Frequency Index of individual factors. According to the values the 1st rank of the severity index among the factors was Design Variation & subsequent ranks were 2nd (Lack of Proper Planning), 3rd (Shortages of Skilled Labour), 4th (Inaccurate material estimate), and 5th (Poor Productivity of Labour), A correlation matrix of all the factors have been developed and accordingly the interdependency among them is known like Inaccurate Material Estimate & Unexpected Weather Conditions have 0.59 correlation value which we all know shows a direct relationship with each other & similarly with Design Variation and location of project constraint has value of -0.478 and thus have a strong relationship between them. It is been then founded or calculated for all the 11 factors from the Correlation matrix which is shown in Table 4. The above results have suggested that one of the key factors in the delays of the project is Design variation or we can say Scope change from the client side. This type of delay is accompanied by several other delays from the other remaining factors as shown with the correlation between all the factors.

5. Conclusion

Reviewing all the projects and project managers who were part of the survey, it has been observed that time overrun is very common for most of the projects and in some cases are accompanied by cost overrun in the majority of the high rise residential construction projects in Noida & Pune. The important factors governing the time over-run or delays are Design variation or scope change, lack of proper planning, shortage of resources & inaccurate Productivity calculation. While the data which were used for this findings are specific to the Indian context, the results generally agree with the findings of the earlier findings of developing countries & thus, its fairly easy to say that on and all this are the major reason for a project to be delayed across the developing countries.

Table 3

	Inaccurate Material Estimate	*Unexpected Weather Condition*	*Shortage of Materials*	*Shortage of Equipment's*	*Shortage of Skilled Labour*	*Inaccurate Productivity Rate calculation*	*Location Constraint of Project*	*Lack of Proper Planning*	*Poor Productivity of Labour*	*Design Variation*	*Inaccurate Productivity estimation of Equipment*
Inaccurate Material Estimate	1										
Unexpected Weather Condition	0.591	1									
Shortage of Materials	-0.091	-0.435	1								
Shortage of Equipment's	0.144	-0.504	0.322	1							
Shortage of Skilled Labour	0.125	-0.347	-0.05	0.0943	1						
Inaccurate Productivity Rate calculation	0.206	0.0154	-0.11	0.3479	0.418	1					
Location Constraint of Project	0.104	-0.181	0.095	0.395	-0.13	-0.0513	1				
Lack of Proper Planning	0.309	0.4775	0.011	-0.0587	-0.40	0.0085	0.102	1			
Poor Productivity of Labour	0.165	-0.261	0.394	0.3022	-0.16	-0.0621	-0.260	0.101	1		
Design Variation	0.154	0.286	-0.3	-0.2494	-0.11	-0.0038	-0.470	0.099	-0.2056	1	
Inaccurate Productivity estimation of Equipment	0.172	0.0821	-0.51	0.1428	0.741	0.4624	-0.057	-0.15	-0.3739	0.198	1

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Further Relevance Analysis of a General PMO Model

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Abstract

In our previous publications at this forum, on the one hand, we introduced and described a comprehensive project management offices (PMOs) model, and on the other hand, we conducted a deeper analysis of two elements of our model. With this series of articles, we are trying to underline the lack of the common categories and the conventional interpretation leading to a diverse discussion on PMOs.
Our suggested PMO model contains six elements formed in a Celtic cross shape. In our latest paper we made a deep analysis of the typology and the service categories. The analysis was not only based on a qualitative literature review, but we have also used the publications as an input for a quantitative analysis.
Continuing this approach in this presentation, we will dive deep in the remaining four elements of our model. The viewpoints and inputs for our analysis:

1. Category of Context (the environment of the PMO): industry and business model dependencies, impact of the organizational project knowledge and culture, PMO trends and PMO surveys from different sources
2. Category of Internal processes (of PMO): attempt to define a common set of process group for PMO, features of portfolio management software products
3. Category Performance (the metrics PMO): success factors, KPIs, expectations, balancing among business, project and operational metrics or emphasizing some of them
4. Category Maturity: compering different PMO and project maturity approaches to set up a practical and general proposal.

Beyond making our model complete with all six elements analyzed, the presentation gives a brand-new part with the analysis of the relationships and dependencies among the elements.

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Keywords: Project management office; evaluation framework; maturity; performance; PMO processses; services; typology

1. Introduction

As a starting point in our earlier publication [1] along with the quest for the determination of a standardized, integrated, and comprehensive framework, we defined a Project Management Office (PMO) model summarizing grounding ideas of our research. This complex PMO model contains six building blocks that describe the complex role and status of PMO within the organization: the context (the environment of the PMO), the typology, the maturity, the internal

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processes of the PMO, the services, and the performance (the metrics of the PMO). This model forms a Celtic cross shape with the main value stream vertically, quality elements horizontally, and important connections among these building blocks called categories. Following the research in our last year publication [2] we focused to show our research method what based on an extensive literature review, and perform the analysis and processing using a mixed, qualitative and quantitative method. In the quantitative part of the research, we analyse the articles as survey elements quantitatively (count them) and build and interpret the model like this. We demonstrated our way of analysis using only two categories from the six ones of the complete model because of size limit of articles here. The result was one hand a unified and complete typology of PMOs according to our qualitative and quantitative deduction and a general service range provided by PMOs. We can summarize our previous result in Table 1 where we show the relations among the found types and defined services groups proving their independency and distinction.

Table 1. Survey elements.

Types/Services	Operation support services	Monitoring and controlling services	Human resource management services	Strategic and portfolio management services
Dedicated PMO	x	x	x	x
Business Unit PMO	x	x	x	x
Enterprise PMO	x	x	x	x
Project Support Office	x	x		
Center of Project Excellence	x		x	

This paper continues the description of our PMO model using the method of article [2] but not going into great detail (again because of the limited space) and defining the categories context, internal/own process, performance, and maturity.

The main purpose of this research series is to provide a developed, integrated new framework for PMOs, which helps to operate and measure PMOs in constantly changing organizations and gives an opportunity to benchmark PMOs to other companies.

2. Context of PMO

A PMO is an integral component of its host organization imbued with specific organizational culture, structural dimensions and functional characteristics and it gives a decisive context for PMO setup and operation. A PMO as a strategic unit and an idea integrated with contemporary organization structure gains mandate from strategy and management expectation. Derived from and depending on the contextual relations, a PMO's mission can be for example (quoted from the literature), organizational innovator, knowledge broker, change and renewal agent, and project performance leader. Your PMO should know its capabilities and possibilities and should know well the organization where the PMO is embedded.

Constitutive but rarely emphasized differentia specifics of an organization is whether it is a project-driven or project-dependent entity. **Project-Driven Organizations** rely on projects directly gaining revenue therefore they are usually more mature from a project culture point of view. **Project-Dependent Organizations** derive most of their revenues from selling products or services and using projects for the development of new products or processes. We highlighted this—in our opinion—fundamental distinction because we have not found this separation during our intensive analysis, in which we collected the research around PMO's contexts, environment and impacts. We planned to write one original essay on the organizational context of PMO and gather explanative elements to the contextual categories and use only small modifications on these categories. But the research gave such rich content about these categories that we had to modify the original list of contextual factors.

We summarize our results in Table 2, showing the major sources of our analysis but we used shortening composing, renaming and interpretation during our work.

Table 1. An example of a table.

Main contextual factors	Explanative elements	Source of elements
Surrounding social system (based on [3])	Organizational level of working (national or international) Laws imposed by the government and other regulatory bodies on the organization financial facilities: stock markets, banks and foreign investors received The sector that the organization works in Cultural status in which the organization is involved	[4]
	Political tension	[3]
	Private or public Geographic region	[5]
Economic sector (based on [6])	Economic tension	[3]
	The sector that the organization works in The organization's competitive situation	[4]
	Application areas	[7]
	Short term, Long term	[8]
The level of complexity of the organization (based on [4])	Size of the organization Size of organizational projects The number and variety of the customers of the organization	[4]
	Matrix or non-matrix organizational structure Size of the organization Internal or external project customers	[6]
	Client relationship tension	[3]
Project dimensions	The number and variety of the organization's customers The role of organization in the project (employer, consultant, contractor)	[4]
	Projects with non-direct financial impacts (improved efficiency, user satisfaction and organizational learning, community benefits, and environment protection) Competitive potential and/or strategic renewal for future business–investment projects Public and non-profit projects	[19]
	Program categories	[7]
	Complexity/Uncertainty dimensions	[9]
Level of project culture (based on [6])	Controlling the project machine tension Standardisation/flexibility tension	[3]
	Relation between organization strategies with PM development Level of organizational project management maturity Methods and technologies used in the project Project management structure in the organization	[4]
	Level of project management maturity	[6]
The philosophy of management (handling events to be resolved) (based on [3])	Business versus Process orientation	[3]
	Organizational culture Delegation of authority in the organization Project management structure in the organization	[4]
	Supportiveness of organizational culture	[6]
	Management mind set	[8]

3. Own Processes – Internal processes of the PMO

PMO processes define its operation

- giving a strong framework and regularity for providing services, serving the project-related activities of the organization
- supporting fact-driven measurement of performance of both business and project activities
- ensuring quality and completeness helping the maturity level of both PMO and organizational project culture

Therefore, processes are the engine of our model and definitely derived from services groups and in relation to PMO type and process environment defined by organizational context.
The starting point of our process review was service groups (from our previous article on this topic [2]), considering the analysed and listed components of these service groups.
Our intensive literature research led to interesting observations:

- considering the PMO service palette, only the portfolio management service has only deeper process level presentations, others are mentioned only at a high level in the publications on the other categories or aspects of the PMO (strategy, maturity, type, etc.)
- Secondly, we recognized the relevant sources of the details of the processes operating in a PMO are not the academic publications, but the practical guides.

Therefore, in our analysis, the practical sources are presented in a higher number than the Examination Content Outline for Project Management Institute (PMI) Portfolio Management Professional (PfMP®) certification or the guide of another project management institution (The Office of Government Commerce, United Kingdom (OGC)) standard Management of Portfolios (MoP™). There was a useful Appendix in Pinto's study [5]about the detailed questions. Again, we got a good and practical input for scanning the PMO process from our earlier work on collecting the PPM and PMO software products and their detailed feature lists and comparisons. Merkhofer [10] gives a good summary of the necessary services, features, processes and we use their tables during our quantitate work.
Beyond these sources, we found ourselves on the academic publications referred to in our article [2] and others mentioned only some examples: [11], [5], [12], [13]. Using similar derivation (composed, renamed, interpretation) to what we demonstrated in our article [2], we can summarize the operating processes at a PMO.
Processes of Strategic and portfolio management services

- - 1- Project component identification, assessment and categorization - 2 - Project component selection and prioritization - 3 - Dependency analysis and portfolio balancing - 4 - Capacity planning and facilitating allocation of organizational resources – 5 - Managing portfolio information flow - 6 - Identifying and managing portfolio changes - 7 - Monitoring and maintaining portfolio-level risks - 8 - Creating and managing a portfolio roadmap and scenarios - 9 - Business and portfolio strategy alignment - 10 - Operating project/portfolio governance framework to ensure management control - 11 - Internal and external Stakeholder Engagement /Management - 12 - Value / Benefit Management - 13 - Decision preparation and recommendations

Operations support services

- - 1 - Ensuring stability and flexibility, adaptation and innovation in project management standards, methodologies, tools – 2 - Implementing and managing project portfolio information systems - 3 - Managing and collecting actual and historical project files and documentation - 4 - Managing interfaces with project environment - 5 - Providing administrative support based on qualitative and quantitative analyses - 6 – Fostering and developing project management awareness and culture within the organization

Monitoring and controlling services

- - 1 - Monitoring and controlling project delivery by phases and milestones - 2 -Tracking and managing project outcome benefits versus business case - 3 - Supporting for contracting, accounting, handling time sheets - 4 - Auditing verification of project acceptance criteria and compliance of project internal processes - 5 - Setting a project measurement system with both hard and soft criteria and dashboards (KPI for resources productivity, project throughput growth) - 6 - Performing a post-completion appraisal on every project - 7 - Supporting issue tracking and estimation of remaining work

Human resources management services

- - 1- Project Track evolution and organize development of project related knowledge - 2 - Select, manage and evaluate project managers - 3 - Provide specialized services for the project manager (consulting, coaching, mentoring, methodology and leadership improvement) - 4 - Assist human resource/staffing assignment and support it with appropriate segmentation - 5 - Use targeted communication to share project knowledge and learning in the organization - 6 - Support project team formation and ensure effective teamwork

4. Performance of PMOs

A study by Gartner in 2010 [14] showed that over 7 years every second PMO failed, the main factor of the failure being not providing enough value for the organization they served. In fact, a well performing PMO is a catalyst for greater efficiency in managing a portfolio of projects: it allows the selection of the right project mix, enables more quality work with fewer resources and less risk. But what does well-performing mean exactly and how can we measure performance?

During our literature review, we found that one of the most common ways to measure performance was the setting up of metrics, so called Key Performance Indicators (KPIs). Example of KPIs include ROI (return on investment), staff retention, and resource utilization. It is absolutely key to select the right indicators, follow them, analyse the results, show and communicate the added value of PMO activities to the stakeholders. With this being set, we can have a clear framework on how [15] the PMO can serve the interests of project managers and stakeholders, and at the same time serve as a strategic framework within the company. With KPIs set, we would then consider that PMOs can clearly prove their added value and contribution. However, it is interesting to see that based on some research, a PMO's performance undoubtedly makes a direct contribution to the organization's return on investment (ROI) [16], while Thomas and Mullaly [17] have shown that it is quite impossible to calculate any direct relationship between project management implementation and ROI. Thomas, J. L., & Mullaly, M. E. bring in the notion of "value" instead of performance in order to capture the business significance of the PMO. Their most significant result is that the notion of fit between the organization and the project management components play the most important role when it comes to obtaining value.

Next to these elements, it is important to consider the link between two other elements of our model: the context of the PMO and PMO type. In comparison with the private sector [18], in the public sector, strategic objectives are not expressed in terms of profit and value to shareholders but with user satisfaction and value for the stakeholders. In the healthcare sector example of Aubry, Richer, Lavoie-Tremblay and Cyr's paper, the problem is very well demonstrated: on the one hand, cost cutting is easily measurable, whereas delivering quality care for the patient factor is much softer. In this case, how can we measure performance?

As far as the performance of the PMO is concerned, rather than providing a common approach for the performance element, we will analyse the connection of the value of the PMO with the PMO context and PMO type.

5. PMO Maturity

Initially, when we started our research, we considered maturity as the element of our model that is there to support continuous improvement of an organization: that can be the internal measurement and goal setting support of the PMO:

But what does maturity mean exactly? The Oxford English Dictionary describes 'mature' as "having reached the most advanced stage in a process", so this means that 'maturity' is the condition of being mature [19]. Maturity can also be a bridge that can compare an organization's actual situation with the best practice from other institutions. Besides that, it can also provide new ideas and improvement initiatives coming from the academic world.

The so-called maturity models were developed by the academic field from the beginning of the 2000s and they were a proven approach for IT leaders to improve the effectiveness of their management processes [20]. There are approximately 60 maturity models that we found, most of them based upon the Software Engineering Institute's Capability Maturity Model Integration (CMMI), whereas the processes identified within them are in the Control Objectives for Information and Related Technology (CobiT) framework from the Information Systems Audit and Control Association.

Several organizations such as Gartner, PWC and ESI have developed their own model, where they defined stages to measure the maturity of the PMO. One of the practical maturity models is the maturity cube [5], which includes a well-established interview questionnaire and a database of the answers from a large number of companies.

Same as for the other elements of our model, our goal was to propose a summary of maturity levels. However, in the case of maturity, we couldn't propose a synthetized view as we see limited difference between the models. Some research has been done in this area. Woerner has shown that there are two general schools of thought: one is process-driven, and the other is business-driven [21], the first associated with the CMM mentioned above, while the business-driven models are focusing more on aligning projects with the organization's goals (tactical to strategic). Cooke-Davies

[22] has defined 3 types of models: those focusing on the project management process, those focusing on the technical process of developing project outcome and those focusing on organizational maturity. As far as maturity is concerned, we consider that it is more interesting to analyse the impact of the other elements of our model on the increase/decrease of the maturity level. We want to emphasize that the maturity level of a PMO doesn't necessarily imply the development state of the organization, although it is interesting to check the dependency of the maturity movements with our other elements. Susan Hostetter and Sherri Norris [23] also emphasized that the movement amongst the maturity levels is dependent on several external factors as well.

6. Conclusion and future work

Based on an exhaustive literature review, we examined the operation of the PMO model we presented, by making our own criteria and using them to analyse and interpret the model. For the sake of completeness, the elements of research so far have to be combined as a whole, and it should be checked against the latest literature. In our research, we examined the connection between the elements of the model and their effect on the content of the constituents. It did not make sense to make a common consolidated list in the case of each model element, but examining the connections was interesting even in these cases (e.g. PMO type/ services, and performance is connected to this).

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Impact of Bonding Capacity on Performance of Construction Contractors and Market

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Abstract

Bonding capacity is an important element in the construction competitive bidding environment. Despite numerous works dedicated to studying different aspects of construction bidding, the impact of bonding capacity on the performance of contractors and market is not explored yet. Using agent-based modelling, this paper aims to examine how bonding capacity affects the financial performance of contractors and market. Agent-based modelling is a powerful modelling tool for simulating the actions and interactions of autonomous agents with the aim of analysing their effects on the system as a whole. The results of this paper show that the extreme limitation of bonding capacity can make the market less efficient. Also, increase in the number of rational contractors as result of a proper bonding capacity limitation restricts the chance of irrational contractors winning from higher uncertainty in cost estimating.

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Keywords: Construction Competitive Bidding; Bonding Capacity; Quantitative Bidding Methods; Simulation; Agent-Based Modeling;

1. Introduction

Contractor default, being unable to complete the project according to the contractual obligations, can significantly affect the outcome of construction projects [1]. As a risk management strategy, construction owners usually protect themselves against the risk of contractor default by transferring this risk to surety companies by mandating the submission of the performance bond by contractors [2]. Performance bond involves three parties: surety company, owner (oblige), and contractor (principal). The bond guarantees to the owner that the contractor will perform the construction project in accordance with the provisions of the contract. If the contractor fails to perform the contract, the owner may call on the surety to step in and complete the project or correct project deficiencies. Because of the considerable consequences of the default, surety companies, owners, and other stakeholders are interested in predictive models that estimate the potential of contractors' default. As a result, several studies in the literature are dedicated to developing models that predict a contractor's default risk [3-9].

Bonding capacity is the maximum amount of surety credit a surety company will provide to a construction contractor. It is referred to as single job limit or aggregate limit and usually expressed in terms of the largest single construction project that the surety company would be willing to issue. In other words, it is the maximum amount of contract

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backlog a contractor can hold. Bonding capacity is also one of the decision parameters in the process of prequalification for determining financial status and stability of a contractor [10].

Despite the great contribution of the previous studies in the literature, the role of bonding capacity (as an internal element of contracting organizations) in the context of competitive bidding has not been explored thoroughly. This can be due to the lack of a high-fidelity model of the construction bidding environment that can incorporate the interrelationships between bonding capacity and other elements of contracting organizations and projects. In this paper, we use Agent-Based Modeling (ABM), as one of the central modeling and simulation tools in the field of computational economics and systems engineering, to examine the impact of bonding capacity on the financial performance of contractors and the market. ABM is a great tool for simulating the micro-behaviors of system components with the aim of analyzing their effects on the system as a whole. This makes ABM the right methodology to address the research question.

2. Methodology

2.1. Agent-Based Model of Construction Bidding

Agent-Based Modelling is recognized as a powerful computational tool for modelling and simulating complex systems in which a set of independent decision makers with different goals and behaviours interact with each other and the system. Due to its holistic approach and capability to deal with complex systems, ABM can be utilized for various research purposes including but not limited to prediction, proof, discovery, education and training [11].

In this paper, we use an agent-based model that reproduces the construction bidding environment with a focus on main decision points of contractors at the organization level. The mechanism of the simulation is that a set of contractors bid on a series of projects randomly generated and introduced into the market. Heterogeneity of contractors is limited to their mark-up decisions as they use different quantitative bidding methods. Similar to the real world contractors that try to learn about their competitors and market conditions and develop a bidding strategy, the simulated agent contractors collect the competitors' past bids and use quantitative bidding methods and determine their optimal bid price. We use a university package of a multimodal simulation software called "AnyLogic" in this paper. AnyLogic is a Java-based platform with the built-in capability to support Monte-Carlo, discrete event simulation, systems dynamics, and agent-based modelling [12].

Projects and Contractors are two main classes of objects in the simulation model. We define contractors as active objects in AnyLogic platform. Each contractor has a number of variables and parameters including bonding capacity, net worth, current work volume, and general & administrative costs. Each contractor also has a number of functions that defines its behaviours at decision or action points. Mark-up selection is the most crucial decision that each contractor has to make. For the purpose of this paper, contractors are set to be homogenous in all attributes except in their bidding methods.

While contractors are active agents due to their ability to learn and make decisions, we define projects as passive agents. Projects are generated consecutively over a simulation period of ten years (520 simulated time units) and are assigned a set of characteristics such as the project budget, the project duration, and uncertainty in cost estimate. Readers can find more details about the developed agent-based model of the construction competitive bidding using AnyLogic in [13-14]. The major assumptions of the paper are the following:

- The developed agent-base model simulates the low-bid lump-sum bidding process.
- Contractors in the market will remain the same throughout the simulation in the experiments.
- All contractors have the same size, initial working capital (which is zero), general and administrative (G&A) costs, cost estimating accuracy, and level of management capability and expertise.
- All contractors have access to their competitors' bidding history.

- All projects have the same budget of $100M.
- To maintain market competition, having a minimum number of two participants is required for a bid to be valid. Otherwise, it will be cancelled.
- The estimated budget for upcoming projects is the same therefore bonding capacity sets a limitation on the maximum number of ongoing projects contractors are allowed to have at any time.

2.2. Quantitative Bidding Methods

In this subsection, we briefly explain the three quantitative bidding methods used in this study to create a heterogeneous market of rational bidders. The goal of a quantitative method is to use competitors' past bids to estimate the optimal mark-up for a contractor. In order to find the optimal mark-up, a contractor needs to maximize its expected profit through solving the following optimization problem:

$$max\ E\left[Profit_{i,k}(x)\right] = [Pw_i(x). Profit_{i,k}(x)] \quad (1)$$

where x (markup) is the decision variable of the problem. The expected profit of contractor i for a given project k is defined as the product of the probability of winning ($Pw_i(x)$) and the profit given a chosen markup x. The bid ($B_{i,k}$), estimated cost ($ES_{i,k}$), markup (x), and profit have the following relationships for a given project k:

$$B_{i,k} = ES_{i,k}\left(1 + x_{i,k}\right) \quad (2)$$

$$Profit_{i,k} = ES_{i,k}. x_{i,k} \quad (3)$$

The three quantitative bidding methods used in this paper use a competitor's past bids in order to characterize her bidding behavior with a probability distribution function of the bid ratio. The bid ratio ($BC_{k,i}$) for a given project (k) is defined as the ratio of the competitor j's bid ($B_{j,k}$) to the contractor's own estimated cost ($ES_{i,k}$):

$$BC_{i,j,k} = \frac{B_{j,k}}{ES_{i,k}} \quad (4)$$

A stable distribution function ($F_X(x)$) of the bid ratio can be constructed if competitor j and contractor i have enough common and available past bids. Given the mean and variance of the distribution, the probability of beating competitor j ($P_{i,j}(x)$) with a given markup (x) can be simply calculated as follows:

$$P_{i,j}(x) = 1 - F_{X_{i,j}}(x) \quad (5)$$

The three quantitative bidding methods used in this paper are using different ways to estimate the probability of winning the bid for contractor i. Friedman [15] assumes the bid ratios of competitors are independent of each other. Hence, the probability of winning the bid (beating all competitors in a low-bid method), can be determined as follows:

$$Pw_i(x) = \prod_{i \in Competitors} P_{i,j}(x) \quad (6)$$

Based on his experience as a principal estimator, Gates [16] developed an empirical equation for determining the probability of winning the contract:

$$Pw_i(x) = \frac{1}{1+\sum_{j \in Competitors}\left(\frac{1-P_{i,j}(x)}{P_{i,j}(x)}\right)} \quad (7)$$

Finally, the *low-competitor model* [17-18] proposes that the only competitor the contractor aims to beat is the lowest competitor. Hence, the low-competitor model is based on collecting the historical data of the lowest bid, the winner, in each competition that contractor i participated in the past.

3. Description of the Simulation Experiments

3.1. Experiment Set A

The purpose of the first set of experiments (A) is to investigate the impact of different levels of bonding capacity on the performance of contractors with different bidding methods. In experiment set A, scenarios A1 to A7 cover a range of limitations on the number of ongoing projects contractors are allowed to have at any time during the simulation (See Table 1). This limitation simulates the bonding capacity of contractors in the real world bidding environment. Table 1 presents the number of ongoing projects allowed for contractors under scenarios A1 to A7. There are nine contractors competing with each other in the market. Contractors 1, 2, and 3 use Friedman model, contractors 4, 5, and 6 use Gates model, and contractors 7, 8, and 9 use Fine model. In the first set of experiments, projects are generated in the market one at a time unit under different scenarios.

3.2. Experiment Set B

The purpose of the second set of experiments is to investigate the impact of different levels of bonding capacity on the performance of both learning contractors and irrational contractors. Table 3 presents the number of ongoing projects allowed for contractors under scenarios B1 to B9. In experiment set B, the market includes a mix of contractors using three main learning algorithms and random markup. Contractors 1 and 2 use Friedman model, contractors 3 and 4 use Gates model, and contractors 5 and 6 use Fine model while contractor 7 and 8 choose their markup randomly from the range of [0% - 10%].

4. Results & Discussion

4.1. Results of the Experiment Set A

The results of the experiment set A are presented in Tables 1 and 2 and Figures 1 and 2. The number of contractors participating in biddings is one of the main factors influencing the level of competition in construction biddings. The higher the number of participants the fiercer the competition would be [19]. As Table 1 presents, the average and the minimum number of contractors in biddings have decreased from scenario A1 to scenario A7 due to imposing the limitation of bonding capacity. This limitation has also caused cancelation of 42 and 182 projects under scenarios A6 and A7 (respectively) where contractors have reached their quota and are not able to participate in some of the biddings, resulted in the cancelation.

One interesting observation presented in Table 2 is that the average markup of all contractors and volatility of the markup market have increased from scenario A1 to scenario A7. Observing Figure 1, the increasing trend of profit per project for all contractors in the market under scenarios A1 to A7 suggests that abundance of projects caused inflation in contractors' submitted markup and consequently their bids. As Figure 2 suggests, imposing the limitation of bonding capacity has decreased the winning rate of Friedman users and the market is divided almost equally among all contractors in scenario A7.

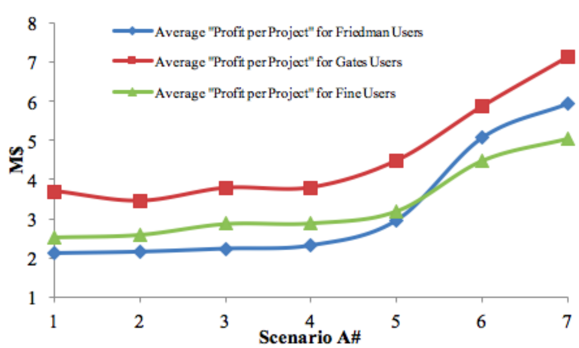

Fig. 1. Profit per Project of Contractors in Scenarios A1-A7

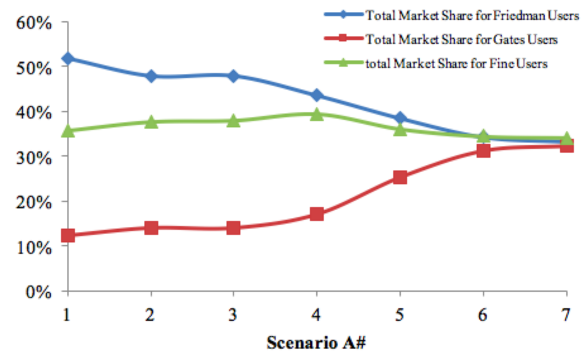

Fig. 2. Winning Rate of Contractors in Scenarios A1-A7

Table 1. Market information of scenarios A1-A7

Scenario	A1	A2	A3	A4	A5	A6	A7
Maximum number of ongoing projects allowed	8	7	6	5	4	3	2
Average number of contractors participating in the biddings	8.9	8.7	8.2	7.6	6.1	3.4	2.1
Minimum number of contractors participating in the biddings	7	7	6	5	3	1	1
Number of cancelled projects	0	0	0	0	0	42	182

Table 2. Average markup of contractors and volatility of the market in scenarios A1-A7

Scenario	A1	A2	A3	A4	A5	A6	A7
Average Markup of Friedman Users	0.81%	0.83%	0.90%	0.96%	1.26%	2.59%	4.43%
Average Markup of Gates Users	2.56%	2.74%	2.71%	2.77%	2.80%	4.07%	5.76%
Average Markup of Fine Users	1.50%	1.43%	1.63%	1.55%	1.53%	1.80%	1.91%
Average Markup of the Market	1.62%	1.66%	1.75%	1.76%	1.86%	2.82%	4.03%
One-Week Historical Volatility of Market Markup	0.82%	0.85%	0.85%	0.88%	0.90%	1.06%	1.18%
Annualized Historical Volatility of Market Markup	5.91%	6.15%	6.13%	6.35%	6.45%	7.63%	8.48%

4.2. Results of the Experiment Set B

The results of the experiment set A are presented in Tables 3 and 4 and Figures 3 and 4. With a few exceptions, trends and orders in the results of the experiment set B are consistent with the ones in the results of the experiment set A. As Table 3 shows, the average and the minimum number of contractors in the biddings has decreased from scenario B1 to scenario B9 due to imposing the limitation of bonding capacity. This limitation has also caused cancelation of 85 and 219 projects under scenarios B8 and B9 (respectively) where contractors have reached their quota and were not able to participate in some of the biddings, resulted in the cancelation.

As Table 8 shows the average markup of all contractors and volatility of the markup market have increased from scenario B1 to scenario B9. According to Figure 3, limiting the number of projects a contractor can have causes inflation in contractors' submitted markup and consequently their bids regardless of contractors' bidding methods. In other words, this limitation restricted the competition and lowered the market efficiency. Also, imposing the limitation of bonding capacity reduces the winning rate of Friedman users and the market is divided almost equally among all contractors as shown in Figure 4.

Finally, by comparing the results of experiment sets A and B, we can conclude that the with the increase in the number of rational contractors the benefits irrational contractors can get unpredictably from higher uncertainty in cost estimating will decrease.

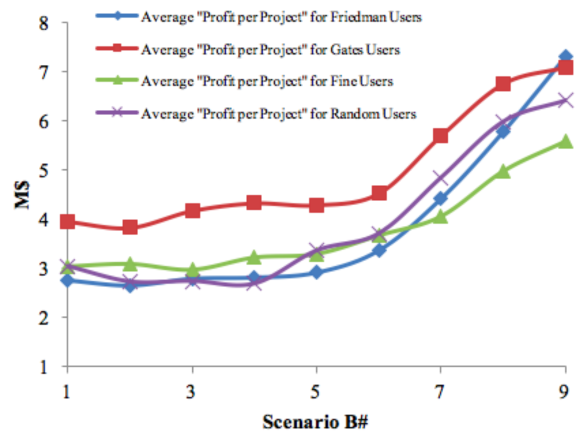

Fig. 3. Profit per Project of Contractors in Scenarios B1-B9

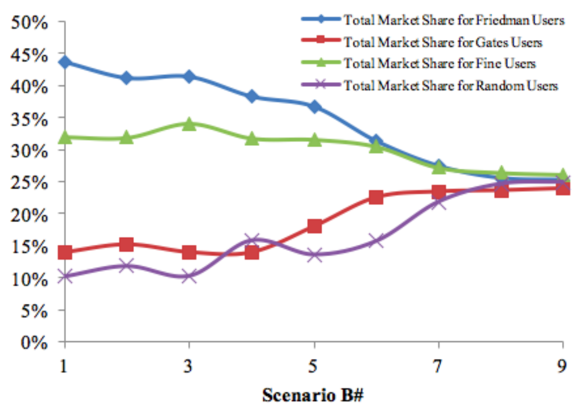

Fig. 4. Winning Rate of Contractors in Scenarios B1-B9

Table 3. Market information of scenarios B1-B9

Scenario	B1	B2	B3	B4	B5	B6	B7	B8	B9
Maximum number of ongoing projects allowed	10	9	8	7	6	5	4	3	2
Average number of contractors participating in the biddings	7.96	7.92	7.79	7.62	7.22	6.25	4.57	2.84	1.88
Minimum number of contractors participating in the biddings	7	7	6	6	5	3	2	1	1
Number of cancelled project	0	0	0	0	0	0	0	85	219

Table 4. Average markup of contractors and volatility of the market in scenarios B1-B9

Scenario	B1	B2	B3	B4	B5	B6	B7	B8	B9
Average Mark-up of Friedman Users	1.10%	1.12%	1.07%	1.15%	1.20%	1.46%	2.18%	3.44%	5.10%
Average Mark-up of Gates Users	2.83%	2.72%	2.79%	2.81%	2.94%	2.95%	3.27%	5.40%	7.87%
Average Mark-up of Fine Users	1.59%	1.55%	1.60%	1.59%	1.52%	1.64%	1.67%	2.04%	1.84%
Average Mark-up of Random Users	5.04%	4.98%	5.19%	4.93%	5.02%	4.93%	4.85%	4.35%	4.41%

Average Mark-up of the Market	1.56%	1.51%	1.52%	1.51%	1.64%	1.93%	2.38%	2.86%	2.93%
One-Week Historical Volatility of Market Mark-up	1.08%	0.94%	0.95%	0.97%	1.07%	1.17%	1.55%	1.58%	1.82%
Annualized Historical Volatility of Market Mark-up	7.76%	6.80%	6.88%	7.00%	7.68%	8.43%	11.18%	11.64%	13.13%

5. Verification & Validation

For verifying the simulation model, we break down the model into several computation steps and verify the programming component of each step, which is easily doable due to AnyLogic's capability of collecting information on any parameter or process at any time through the simulation. We compute the corresponding calculations of all the process steps manually, compare and verify with the model calculations for some specific bidding cycles in several simulation runs.

For validating the simulation model, we use parameter variability (sensitivity analysis). We examine how uncertainty in the values of the key input parameters (such as project budget) can impact the model output and whether the outcomes are within a reasonable and expected range. Considering the capability of the developed agent-based model in AnyLogic, we employ different distributions for project budget, estimated duration, actual cost, and actual duration in addition to the fact that all experiments are conducted under different scenarios in order to make sure results are consistent. We also employ robustness analysis or extreme condition test in order to observe the response of the model to drastic changes such as complete failure in securing a project for a long period of the simulation or unexpected success in early bids. For example, the first 10 projects are given to a specific contractor and then the simulation was run as normal. We observe no significant change in the results.

6. Conclusion

Bonding capacity is an important element of construction contractors' organization as it is used for assessing financial status and stability of a contractor. Despite an extensive body of works in the area of construction bidding, the impact of bonding capacity on the financial performance of contractors in the bidding environment is not explored yet. In this paper, we use an agent-based model of construction bidding environment in order to investigate the impact of bonding capacity on contractors with different bidding strategies. Results indicate that in a market consisting of rational contractors imposing the limitation of bonding capacity can make the market less efficient: it decreases the gap between more effective and less effective contractors and increases average profit per project across the market. Also, an increase in the number of rational contractors would limit the chance of irrational contractors winning due to the variations of cost estimating among contractors.

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Implementing Progressive Design Build, A Case Study: UW West Campus Utility Plant

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Abstract

Design-Build (DB) contracts have been used for many years in the United States of America. The award of a DB contract frequently relies on evaluating which DB team provides for the best value through a multi-criteria evaluation process with price being one of the most important criteria for team selection. To ensure project success, the owner usually has to spend adequate efforts and time during scoping and early design to prepare a program, scope, and budget, which are defined enough to undergo procurement and price generation. This, however, has become a potential burden for the owner, and may lengthen the project development duration. As an alternative to traditional Design-Build, Progressive Design-Build (PDB) provides for the selection of the DB team prior to deciding the program and/or budget for the project. PDB has the advantage of maintaining a single point of accountability and allowing to select a team based mainly on their qualifications with a limited price consideration. Under PDB, the selected team will work with the agency's stakeholders during the early design while helping the owner to balance scope and budget. The key to understanding PDB, however, lies in the ongoing and complete involvement of the owner in the early design phase. Due to the differences between PDB and the other project delivery methods (e.g., traditional DB), several factors must be considered carefully to assure the successful implementation of PDB. However, information on PDB is lacking because of its novelty. This paper aims to investigate the implementation of PDB by conducting a case study of the University of Washington's pilot PDB project for completing the West Campus Utility Plant (WCUP). The project's entire delivery process and organizational structures are summarized and presented.

Keywords: Progressive Design Build; Project Delivery Method

1. Introduction

Design-Bid-Build (DBB) is the project delivery method traditionally used in public works. However, its efficiency has been questioned due to its vulnerability to construction claims, busted budgets and schedule delays. Design-Build (DB) is one of the alternative methods designed to overcome the inherent drawbacks of DBB. In the United States, DB has been used by public owners for decades. In a DB project, a single entity contracts with the owner to provide design and construction services. The solicitation is usually based on one of three approaches, including low bid, one-step best value, and two-step best value [1], and the bidding evaluation focuses on two aspects primarily – qualifications and price. Also, the owner usually contracts with an independent design consultant to develop conceptual design

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necessary to the issuance of a Request for Qualifications (RFQ) and a Request for Proposals (RFP). Upon response to the solicitation, the winning team is selected based on the design proposal and price. A traditional DB requires the RFP to be as specific as possible to explicitly state the project requirements, which is usually the last chance for the owner to clarify their expectations [2].

The success of a DB project relies highly on the owner's early design. In the RFQ phase, the early design documents provide prospective contractors with the information necessary to assemble the right team for the competitions. In the RFP phase, a comprehensive early design package helps DB teams eliminate confusions or misunderstandings and start from the same basis of design. Additionally, a well-designed preparatory document can reduce the uncertainties and the potential problems of subsequent change orders. Therefore, in order to ensure the project success, the owner usually has to spend adequate efforts while developing the early design documents so that they provide for a clearly defined program, scope, and budget. This, however, has become a potential burden for the owner, and to a certain extent, has lengthened the overall project duration.

Recently introduced in procurement code, Progressive Design-Build (PDB) is an emerging alternative to the traditional DB, which determines the DB team prior to setting the program and/or budget for the project. PDB maintains a single point of accountability for the team selection and evaluates competing teams based on their qualifications with a limited consideration of price factors. The selected DB team works with the owner to complete the early design, while helping to balance scope and budget. The key to understanding PDB, however, lies in the on-going and complete involvement of the owner in the design phase. The owner should be aware that every decision has an implication in terms of costs, and that any change to these decisions potentially creates a new cost. Knowing the costs associated with the project in a timely manner increases the owner's perception of the contractor as an ally, and the team is no longer seen as always ready to take advantage of the circumstances in order to increase its profit margin. Innovation is fuelled by a collaborative environment in PDB, and because of the continuous involvement of the owner, it is possible to obtain feedback and directives on time, during both the design and construction phases.

To improve understanding of PDB, the authors have developed a case study paper based on the pilot implementation of PDB by the University of Washington for the delivery of the West Campus Utility Plant; thus this paper describes the procurement process of this pilot PDB project. First, we discuss the differences between PDB and traditional DB; next, the case study is presented; finally, lessons learned are listed.

2. Distinguishing PDB From Traditional DB

Under traditional DB, some teams are not selected due to the relative high price of their outstanding design alternatives. This is especially true when the price criterion is highly weighted, such as in low bid procurement. On the other hand, PDB allows the owner to choose the most appropriate team based primarily on qualifications and to complete the design together with the selected team. The major differences between PDB and traditional DB derive from three aspects, including its solicitation process, contractual structure, and risk allocation.

In terms of the solicitation, a complete basis of design is no longer necessary prior to the team selection for PDB projects. In the RFP phase of the traditional DB project, the shortlisted design-builders submit a detailed technical proposal with a design sufficient to define scope and price. The proposal is typically accomplished based on a baseline design provided by the owner, with technical specifications. However, this solicitation process conversely increases the owner's burden, as it requires the owner to spend more time and money upfront to develop a basis of design and it also places higher responsibilities for the cost of changes on the owner. Moreover, the traditional DB also has a potential negative impact on innovation since the designer does not have discretion over the whole design. PDB deals with these problems by involving the DB team in the design phase from the very beginning. Very low or even no design effort is required before the contract is awarded, which allows the owner to save time and money through a streamlined procurement process. Additionally, it shortens the procurement time, as the candidate teams no longer need to develop a portion of the design in support of their proposal. From the owner's point of view, the preparation costs and time for RFQs and RFPs are relatively low in PDB and the evaluation is easy due to the qualification-based selection (QBS). From the perspective of DB teams, PDB is more attractive because it requires less effort (e.g., cost and time) to respond to the solicitation.

In terms of contractual structure, PDB projects usually have simpler contracts comparing to traditional DB projects. Commonly, a PDB project relies on two separate contracts, including a Preliminary Agreement and a Construction Contract; this creates a two-phased approach. Initially, the Preliminary Agreement is executed with the main goal of advancing design to a level that can be priced. The target level of design is typically around the traditional Design Development (DD) stage, but this can change as agreed by both parties. While the Preliminary Agreement is in place, project accounting is open-book, so the DB team is compensated on an hourly basis to develop design documents enough to define scope and price. During this phase, the design-builder also performs a wide range of pre-construction services, including constructability reviews. Once the design evolves to a level leading to a mutually agreed price, the execution of the Construction Contract initiates a separate contracting phase, which is based on the deliverables from the Preliminary Agreement. Its scope is similar to a traditional DB contract, in short to complete the design and build the project at the agreed price. Some agencies execute a separate contractual document for this phase; others amend the Preliminary Agreement. The choice between these two pathways appears dependent on both agency's preferences and project type and complexity. Since the DD documents were developed collaboratively and provide only for an intermediate level of design completeness, the owner may bear additional risks due to varying interpretations of the scope during the second contractual phase.

The Preliminary Agreement is awarded based primarily on qualifications, while the second contract can be based on two pricing methods: cost plus with Guaranteed Maximum Price (GMP) or Lump Sum (LS). The level of design detail used in price estimation is typically higher in PDB (around 60%) than in traditional DB (approximately 35%). Under PDB, the collaborative design process continues into the second phase since the design needs to be completed and the owner is deeply involved. During this second contract phase, the owner participates in decisions about the scope while relying on price information provided by the DB team. Since the price has already been set into the Design-Build contract, these decisions typically include some scope trade-offs. The owner can also use the project contingency and change order process to add or modify specific scope elements, although the goal of the first contract phase (i.e. the Preliminary Agreement) is to minimize the need for such change orders. The open-book contractual terms allow for owner participation and flexibility in on-going design, redesign, scope additions, re-estimates, and value considerations [3]. Under PDB, as the design progresses, the DB contractor can procure subcontractor design assistances and bids, thus providing the owner with a more firm cost for major elements of works [4].

In terms of responsibility and risk, the owner has a fairly large responsibility in PDB projects due to the intense involvement during the entire process, especially for the design phase. Thus, it requires the owners to be well informed regarding the project needs and requirements. While PDB does not require the owner to have a basis for design in the RFP, doing so can help simplify the owner's responsibilities during the design collaboration of the Preliminary Agreement. A good basis of design in the RFP can be particularly valuable when there are multiple stakeholders within the owner's organization who all have expectations that need to be preserved. It can alleviate concerns about certain project characteristics being lost during the busy and typically time constrained design phase.

3. The PDB Case Study

To provide a comprehensive understanding of PDB and contribute to best practices for future implementation of PDB, a case study of a pilot PDB project in Washington State has been conducted through analysing project documents, attending project meetings, and conducting semi-structured interviews with the different stakeholders (e.g., project owners and contractors).

3.1. Project Description

In 2013, the University of Washington (in Seattle) awarded a project to build a new utility plant, named the West Campus Utility Plant (WCUP), which serves as an extension of the University's Power Plant. The WCUP is intended to produce chilled water to meet both process and comfort cooling needs for a variety of facilities in the West and South Campus areas of the University. The plant is also expected to generate electrical power to meet emergency/standby needs.

The WCUP development was planned to occur in two utility expansion phases. In the first phase, a plant containing generators, chillers, cooling towers and associated equipment in order to produce 6 megawatts (MW) of emergency power and 4,500 tons of chilling capacity was built and placed in operations. A second phase foresees the opportunity to approximately double both the production of power and chilling capacity (i.e., 12 MW of emergency power and 10,500 tons of chilling capacity). During the first phase, a building able to host the two utility expansion phases was built. This case study is based on the first phase of the project.

3.2. The Delivery Process

Due to the potential changes in the future plans of the utility expansion, there was a need for a more flexible delivery method. In this project, the owner (UW) selected a highly collaborative PDB process that was new to both the University and the state.

PDB in the WCUP is preceded by a planning phase and follows with a solicitation phase with two sub-phases, including an RFQ phase and an RFP phase. Each phase includes several activities, and the transition from one phase to another is marked by the achievement of a milestone, which usually consists of the issuance of a procurement or contractual document. Team qualification is the only criterion used in the RFQ phase, while the RFP phase is based on qualifications, the proposed approach to the project, and the legally required price-related factor. The DB team has been decided after the solicitation phase. The owner and the selected team then proceeded to signing two contracts, named as preliminary agreement and construction contract respectively, concerning the completion of the design and construction. An overview of the delivery process is illustrated in Figure 1.

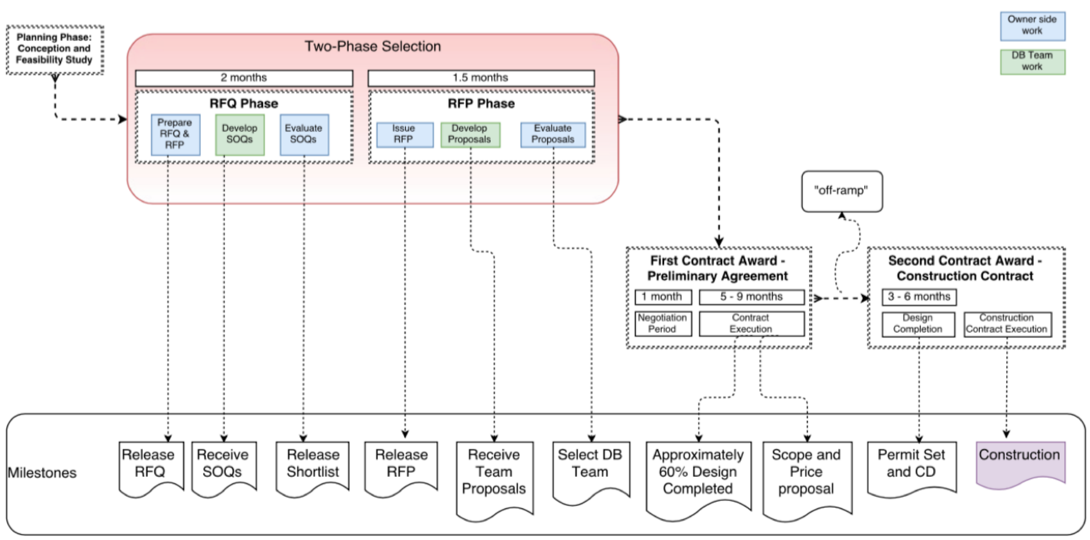

Fig. 1. Overview of procurement process with phase durations and milestones

3.2.1. The Planning Phase

The planning phase happens before the solicitation. Initially, the project needs and utility demands were identified by the UW Facilities Services (FS) department. Later on, the Capital Planning and Development (CPD), the organization responsible for managing capital projects at the UW, initiated a feasibility study and hired consultants to evaluate the feasibility of augmenting the campus emergency power and chilled water capacities and various sites. Based on the feasibility study, the CPD and FS applied to the UW's Board of Regents (BoR) for project authorization. This request contained a project budget (i.e. estimated total project cost), scope of work, and schedule. The BoR approved the authorization request in 2013 and confirmed the use of PDB as the delivery method. A project manager from the CPD was assigned as the main contact throughout the life of the project and works closely with the construction entity to ensure schedule and budget adherence. The manager was responsible for organizing and administering the project from the conception to the completion.

3.2.2. The Solicitation Phase

Similar to the traditional DB, the solicitation process of the WCUP project included two sub-phases, including a RFQ and a RFP.

RFQ Phase

To determine project priorities and develop a risk management plan, a policy analysis was first conducted by the CPD contract/legal manager and directors. The RFQ documents were developed after this initial policy analysis. The purpose of the RFQ was to generate a shortlist of DB teams entering the RFP phase. The RFQ phase can be further divided into three major steps, including preparation of RFQ documents, interaction with the DB teams, and evaluation of the Statements of Qualification (SOQs).

In the RFQ documents preparation step, the project directors and managers were responsible for developing an initial RFQ draft containing the weighted selection criteria and a description of the process. An industry review (through the Daily Journal of Commerce) was then conducted to recruit suggestions, and based on the feedback the RFQ was revised and finalized. The milestone of this step was the issuance of the RFQ. Different from the past, this RFQ focused more on the qualification of the participating teams.

In the step of interacting with DB teams, the participating teams developed their SOQ based on the issued RFQ. Unlike other projects, the WCUP included no collective meeting between the interested teams and the owner. If the DB team requested further clarification, they were allowed to consult with the unique representative assigned by the owner. The step ended with the candidate teams submitted the SOQs within the prescribed time limits.

In the evaluation step, the Selection Committee (SC), assembled in the beginning of the RFQ phase, evaluated the SOQs through the attribution of a score for each criterion. The points were added up to rank the teams. The three highest scoring teams were shortlisted and invited to participate in the RFP phase.

RFP Phase

In the RFP phase, the shortlisted teams were not required to design or price an actual proposal, instead, the WCUP project emphasized that the teams should prove their qualifications and the approach for collaboration. Similar to the RFQ phase, the RFP also consisted of three steps, including preparation of RFP package, proposal development, and proposal evaluation and selection.

An RFP package, which contains a) RFP document, b) price factor form, c) two contracts (i.e., preliminary agreement and construction contract), d) general conditions, and e) general requirements, was first prepared by the owner (UW) to explicitly state the project requirements and expectation. According to the characteristics of the PDB, the design requirements in the RFP were relatively brief compared to the traditional DB. The RFP also prescribed the procedures and deadlines for submitting the proposals, and the evaluation process was clarified, including the evaluation criteria with the corresponding weights. The main criteria are summarized in Table 1.

The initial six criteria listed in Table 1 were considered of greater importance and were assigned higher weights. The price factor (Criterion 11) did not carry a heavy weight; still, it indicated a price range for the price proposed by the winning team for the second contract. Once the preparation step was completed, the RFP package was released to the three eligible candidates.

In the proposal development, the owner arranged individual meetings with shortlisted teams, referred as proprietary meetings, to help the team get clarification on both the evaluation criteria and the selection process. The shortlisted teams would have the chance to present their preliminary proposals and communicate with the University's

Architectural Commission, the SC and other executives. The owner posted pertinent addenda online to ensure each team competing with the same level of information.

Table 1. The main proposal evaluation criteria in the WCUP project

	Evaluation Criteria
1	Essential characteristics of, and general approach to, managing the DB project (e.g., the understanding of PDB method)
2	Engineering approach (e.g., the team's strategy to develop the project in terms of functionality and quality of the work)
3	Approach to building architecture and urban design (e.g., how to stick to the UW architectural goal)
4	Management and approach to design development (e.g., the means of interaction within the team and between the team and owner during the design)
5	Management and completing approach to design and construction (e.g., how changes during the project design and construction will be managed)
6	Management and approach to commissioning and training (e.g., how the team will train the UW staff to allow the smooth transition to operations)
7	Ability to meet time and budget requirements
8	Acceptance of contract, bonding and insurance (as a Pass or Fail decision)
9	Workload factor (e.g., impact of activities outside the project that may affect the team's ability to carry out the work)
10	Location of the team (as it may impact the communication capability during the work)
11	Price factor, including the percentage rate for Overhead and Profit of the DB contractor
12	MBWE (Minority and Women owned enterprise) outreach plan

In the evaluation step, the shortlisted teams submitted their proposals in two different envelopes – one containing bonding and insurance letters, and price factor; and another containing the answers to the remaining criteria. The UW's project managers scheduled the deadline of the proposal submission, collected the responded proposals, discarded the team that failed to meeting Criterion 8 (P/F) with the independent financial consultant, and then forwarded the eligible team proposals to the SC who would decide the team's score for each criterion and rank the teams based on the sum of scores. The winning team was determined based only on the evaluation scores.

3.2.3. The Contracting Phase

The Contracting phase consisted of two sub-phases, including a Preliminary Agreement and a Construction Contract. The first contracting phase started by a negotiation between the owner and the winning team and followed by the execution of the Preliminary Agreement. The Agreement required the owner and the DB team to collaboratively generate a Work Plan which included (1) a scope of work and a schedule of activities; (2) the anticipated hours needed to complete each activities; (3) the individuals who will be responsible for each activity and the corresponding hourly rates; and (4) the deliverables – approximately 60% design with a design narrative and a price. The Preliminary Agreement also prescribed the deadline and the maximum payment, which, however, can be adjusted by mutual agreement between the owner and the DB team. If the owner failed to reach an agreement with the highest scoring finalist, the owner could consider contracting with the next highest scoring finalist. In the studied case, the selected DB team was composed of a general contractor (GC) and a number of design and engineering firms. The GC was the leader of the team and entered into separate contracts for architectural design and for engineering design. Additionally, the GC contracted with the major mechanical and electrical subcontractors and all other subs. As such, despite the collaborative team atmosphere where the owner works with all the designers, these entities are contracted directly with the GC.

The second contract dealt with the completion of the design and the construction phase. A lump sum was used in this project. Two different scenarios might happen in this phase. On one hand, the owner and the same DB team from the Preliminary Agreement would continue to sign the second contract and complete the project design and construction collaboratively. On the other hand, an off-ramp clause could be exercised if the owner and the original team failed to reach an agreement regarding the final price of the project or other terms in the second contract. By exercising the off-ramp, the owner could use alternative approaches to complete the project. Under the off-ramp, language in the Preliminary Agreement allowed the owner to use design documents provided by the original team. Still, the owner had the right to hire another team to complete the project or execute the project with another delivery method such as DBB. In the WCUP project, the owner continued to work with the original DB team to complete the project under PDB, and the off-ramp option was not used.

3.3. Project Evaluation

As the first PDB project to both the UW and the Washington State, the WCUP harvested a satisfactory result from the perspectives of time, budget, and collaboration. Overall, the reactions/feedbacks from all the stakeholders to PDB were positive. The owner and the DB team successfully built a good trust between each other and maintained healthy relationships among all participants. There were no hard disputes during the project delivery period, and the process of figuring out issues with contractors and subs went efficiently.

However, some issues were revealed during the process. From the owner's perspective, the design and collaboration process was generally rigorous, but the cost estimating piece was not applied effectively as expected. For example, different stakeholder groups needed to collaborate with their respective design professionals in their area of focus or expertise, but this dissection poses challenges for the entire design process, which is difficult to be inclusive and efficient.

4. Conclusion

As an emerging alternative to Design-Build delivery method, Progressive Design-Build (PDB) provides for the selection of the DB team prior to setting the program and/or budget for the project. PDB allows selecting the DB team based mainly on qualification with a limited price consideration. To have a comprehensive understanding of PDB, this paper conducted a case study based on a pilot PDB project, West Campus Utility Plant (WCUP), which is the first PDB project to the Washington State. The project's entire delivery process (e.g., planning, solicitation, and design and construction), organizational structures, and outcome are summarized and presented in this paper. The learned lessons from the project are also summarized. The findings from the WCUP project are intended to contribute to best practices for future PDB implementation.

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Improved Unbalanced Bid Detection Model

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Abstract

Detection of unbalanced bids is crucial for owners because selecting an unbalanced bidder as the contractor may bring about cost overruns. There are two main types of unbalanced bids, namely, mathematically and materially unbalanced bid. This study mainly focuses on the second type, where a contractor tends to increase the unit prices of items whose quantity was somehow underrated by the owner's team. This study proposes a modification to a model that was developed to assist owners in detecting unbalanced bids. The major difference between the proposed model and the previous one lies in the grading system of detecting the unbalanced bids. In the proposed model, eight different grading systems are used in detection of unbalanced bids, whereas the previous model consisted of five grading systems. The final score of each bidder is calculated by assigning weights to these grading systems. Bidders are evaluated not only according to the offered bid prices, but also according to the calculated final scores. The applicability of the proposed approach is presented along with an illustrative example. It was observed that the proposed model detected the unbalanced bid, which attains the lowest final score. The proposed model represents a marked improvement on existing practice and provides owners with a new perspective in detecting unbalanced bids. Armed with such a tool, it may be easier for owners to protect themselves from the risk of unbalanced bids.

Keywords: Unbalanced bid; detection model; grading system; owner; case study.

1. Introduction

Cost overrun is one of the main problems frequently encountered in construction projects [1]. From the owner's perspective, one of the effective ways to prevent cost overrun is to detect unbalanced bids during the bid evaluation phase. Manipulation of bid items' prices without changing the total bid price can be called as "unbalanced bidding" [2]. There are two main methods of unbalancing a bid: mathematically (front-end loading) and materially (quantity error exploitation) [3, 4]. Front-loading is a method that increases the unit prices of the activities scheduled to start in the early phases of the project while reducing the unit prices of the activities scheduled to start in the later phases. Thus, contractors can achieve better cash flows and higher profits while reducing their financial risks in the project [3]. End-loading is a method that is applied by increasing unit prices of activities in the later phases of the project. End-loading is a less-used method compared to front-loading. End-loading method is usually used for taking advantage of the escalation in countries with high inflation rates [4]. Quantity error exploitation is a method applied by increasing

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the unit prices of the activities in which actual quantities are expected to exceed the estimated ones, while decreasing the unit prices of the activities that are overestimated [5].

Unbalanced bidding in the construction industry have been discussed by several researchers thoroughly [3]. Although detecting unbalanced bids created by quantity error exploitation is more difficult for owners [6], and there are few studies that help owners to detect and prevent unbalanced bids, most of the studies in the literature are conducted from the perspective of contractors [2, 4-9]. Therefore, this study focused on the detection of unbalanced bids created by quantity error exploitation in unit price contracts. For this purpose, after reviewing the existing models in the literature, an advanced unbalanced bid detection model was proposed by improving the model developed by Polat et al., (2018) [10]. The proposed model uses eight different grading systems in detection of unbalanced bids, whereas the previous model consisted of five grading systems. Owners may assign different weights to these grading systems according to the characteristics of their projects. After assigning weights to the grading systems, the final scores of each bidder can be calculated. All bidders can be evaluated not only according to their bid prices but also according to the calculated final scores. An illustrative example is presented to check the applicability of the proposed model in construction projects. The findings of this study indicated that the proposed model provided a marked improvement compared to the previous model. It also provides owners with a new perspective in detecting unbalanced bids during the bid evaluation phase.

2. The Improved Unbalanced Bid Detection Model

The objectives of this study include: (1) defining new grading systems to extend the existing approach in detection of unbalanced bids, (2) validating the new grading systems through an illustrative example. In order to achieve these objectives, the model developed by Polat et al., (2018) was modified by adding new grading systems. For the new grading systems, major and minor bid items have been defined. If a bid item's total price is equal to or greater than five percent of the construction cost estimated (ECC) by the owner, this bid item called as a “major bid item”. On the other hand, if a bid item's total price is less than five percent of the ECC, this bid item called as a “minor bid item”. Polat et al., (2018) described the existing grading systems for detection of unbalanced bids. The modified approach proposed in this study adopts the same grading systems used by Polat et al., (2018), but the following grading systems are added for detection of unbalanced bids.

Sixth grading system: The main idea behind this grading system is to compare the unit price of each major activity i_{mj} ($i_{mj} = 1, 2, \ldots, n$) ($bupi_{mj}$) offered by each bidder with the ones estimated by the owner ($oupi_{mj}$). The ratio of each major activity's total price (or_{imj}) estimated by the owner in the ECC is calculated using Equation 2. In this grading system, the comparison ratio (r_6) is calculated using Equation 1. Bidders receive a grade for each major activity (g_{6imj}) based on the intervals given in Table 1. The total score received from the sixth grading system (BTS_6) is found by using Equation 3, where g_{max} is the maximum value of the sixth grading system (g_{max} =42).

$$r_6 = \frac{bup_{i_{mj}}}{oup_{i_{mj}}} \tag{1}$$

$$or_{i_{mj}} = \frac{oup_{i_{mj}} \times q_{i_{mj}}}{ECC} \tag{2}$$

$$BTS_6 = \frac{\sum_{i_{mj}=1}^{n} (or_{i_{mj}} \times g_{6i_{mj}})}{\sum_{i_{mj}=1}^{n} (or_{i_{mj}}) \times g_{\max}} \times 100 \tag{3}$$

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Seventh grading system: The main idea behind this grading system is to compare the unit price of each major activity (bup_{imj}) offered by each bidder with the average of unit prices (aup_{imj}) offered by n number of bidders. The average unit price of each major activity and the comparison ratio (r_7) are calculated using Equation 4 and 5, respectively. Bidders receive a grade (g_{7imj}) according to the comparison ratio obtained for each major activity (see Table 1). Then, the total score received from the seventh grading system (BTS_7) is found using Equation 6, where g_{max} is the maximum value of the seventh grading system (g_{max}=42).

$$aup_{i_{mj}} = \frac{bup_1 + bup_{2+} ... + bup_n}{n} \tag{4}$$

$$r_7 = \frac{bup_{i_{mj}}}{aup_{i_{mj}}} \tag{5}$$

$$BTS_7 = \frac{\sum_{i_{mj}=1}^{n} (or_{i_{mj}} \times g_{7i_{mj}})}{\sum_{i_{mj}=1}^{n} (or_{i_{mj}}) \times g_{\max}} \times 100 \tag{6}$$

Eighth grading system: The main idea behind this grading system is to compare the ratio of sum of the major activities' total prices (br_{imj}) to that of minor activities (br_{imn}) with the ones (or_{imj}, or_{imn}) estimated by the owner (see Equations 7-8). The comparison ratio (r_8) is calculated by Equation 9. Bidders receive a grade ($g8$) according to the comparison ratio presented in Table 1. The total score for the eighth grading system (BTS_8) is calculated using Equation 10, where (g_{max} = 42).

$$br_{i_{mj}} = \sum_{i_{mj}=1}^{n} (bup_{i_{mj}} \times q_{i_{mj}}) \ , \ br_{i_{mn}} = \sum_{i_{mn}=1}^{n} (bup_{i_{mn}} \times q_{i_{mn}}) \tag{7}$$

$$or_{i_{mj}} = \sum_{i_{mj}=1}^{n} (oup_{i_{mj}} \times q_{i_{mj}}) \ , \ or_{i_{mn}} = \sum_{i_{mn}=1}^{n} (oup_{i_{mn}} \times q_{i_{mn}}) \tag{8}$$

where q_{imj} is the quantity of major activity i_{mj} and q_{imn} is the quantity of minor activity i_{mn}.

$$r_8 = \frac{(br_{i_{mj}} \div br_{i_{mn}})}{(or_{i_{mj}} \div or_{i_{mn}})} \tag{9}$$

$$BTS_8 = \frac{g_8}{g_{\max}} \times 100 \tag{10}$$

For all grading systems, a comparison rate is calculated. Bidders receive grades depending on these ratios. The grading table (Table 1) allows the owner to evaluate the bidders objectively. In grading systems 6, 7, and 8, a comparison rate that is higher than 1.050 corresponds to the lowest grade (g_{min}=1), whereas a comparison rate lower than 0.950 corresponds to the highest grade (g_{max}=42). Finally, each bidder's final score can be calculated by assigning weights to each grading system according to a preferred criterion (Equation 11). The evaluation of the bidders will be based on these final scores.

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$$FS = \sum_{j=1}^{8} (w_j \times BTS_j) \tag{11}$$

where w_j is the weight for the j^{th} grading system and BTS_j is the total score for the j^{th} grading system.

Table 1. Grade values for grading system 6,7 and 8.

Comparison Ratio	Grade	Comparison Ratio	Grade	Comparison Ratio	Grade	Comparison Ratio	Grade
r ≤ 0.9	42	0.950 < r ≤ 0.955	31	1.005 < r ≤ 1.010	20	1.060 < r ≤ 1.065	9
0.900 < r ≤ 0.905	41	0.955 < r ≤ 0.960	30	1.010 < r ≤ 1.015	19	1.065 < r ≤ 1.070	8
0.905 < r ≤ 0.910	40	0.960 < r ≤ 0.965	29	1.015 < r ≤ 1.020	18	1.070 < r ≤ 1.075	7
0.910 < r ≤ 0.915	39	0.965 < r ≤ 0.970	28	1.020 < r ≤ 1.025	17	1.075 < r ≤ 1.080	6
0.915 < r ≤ 0.920	38	0.970 < r ≤ 0.975	27	1.025 < r ≤ 1.030	16	1.080 < r ≤ 1.085	5
0.920 < r ≤ 0.925	37	0.975 < r ≤ 0.980	26	1.030 < r ≤ 1.035	15	1.085 < r ≤ 1.090	4
0.925 < r ≤ 0.930	36	0.980 < r ≤ 0.985	25	1.035 < r ≤ 1.040	14	1.090 < r ≤ 1.095	3
0.930 < r ≤ 0.935	35	0.985 < r ≤ 0.990	24	1.040 < r ≤ 1.045	13	1.095 < r ≤ 1.100	2
0.935 < r ≤ 0.940	34	0.990 < r ≤ 0.995	23	1.045 < r ≤ 1.050	12	1.100 < r	1
0.940 < r ≤ 0.945	33	0.995 < r ≤ 1.000	22	1.050 < r ≤ 1.055	11		
0.945 < r ≤ 0.950	32	1.000 < r ≤ 1.005	21	1.055 < r ≤ 1.060	10		

3. Illustrative Example

An illustrative example used by Polat et al., (2018) is presented to validate the applicability of the proposed model in construction projects. The presented example compromises 72 activities, and 5 out of 72 activities are identified as "major activities" while others are identified as "minor activities". The unit price of each activity estimated by the owner are taken from "The Construction and Installation Unit Prices Book" published by the Turkish Ministry of Environment and Urban Planning. The units, quantities, unit prices of these 72 activities estimated by the owner (O) and offered by 8 bidders (B) are presented in Table 2.

Table 2. Input data for illustrative example.

Act. ID	Unit	Quantity	Unit Prices (TL – Turkish Liras)								
			O	B_1	B_2	B_3	B_4	B_5	B_6	B_7	B_8
A_1	m^3	700	14.38	14.75	13.07	15.50	15.56	14.92	13.64	14.88	14.66
A_2	m^3	365	38.83	41.91	41.25	42.38	35.58	41.11	38.14	40.41	36.32
A_3	m^3	850	2.84	3.08	2.59	2.96	2.63	2.98	2.84	2.86	2.68
A_4	m^3	736	4.83	5.29	4.57	5.27	5.15	4.36	4.46	4.62	4.72
A_5	m	198	67.70	65.94	63.94	74.14	65.43	69.76	68.75	69.39	62.33
A_6	m^3	59	31.88	29.82	28.96	29.66	29.41	33.12	29.21	28.89	29.34
A_7	m^3	150	14.19	13.60	13.21	14.34	13.67	13.78	15.17	13.64	15.11
A_8	m^3	90	29.19	26.97	28.68	29.95	31.42	30.40	31.12	29.52	30.38
A_9	m^3	2000	178.63	170.44	183.53	173.77	166.04	189.94	187.99	175.84	169.66
A_{10}	m	1200	335.43	330.84	362.48	336.29	333.25	322.75	318.94	329.43	353.08
A_{11}	m	650	68.40	65.53	74.79	69.38	63.26	64.79	69.13	72.10	73.25
A_{12}	m^3	350	52.20	51.26	47.00	54.89	56.72	47.53	54.14	52.51	56.04
A_{13}	m^3	100	86.29	84.53	92.11	85.72	91.16	88.14	85.52	88.90	82.79
A_{14}	m^3	360	121.63	112.82	133.19	131.99	130.73	122.52	128.27	111.87	124.88
A_{15}	m	36	29.19	29.64	28.97	30.16	27.98	28.77	31.89	29.44	27.92
A_{16}	m	40	33.40	35.59	34.05	32.36	36.04	35.12	36.57	32.56	36.23
A_{17}	m^2	1000	22.18	20.98	23.41	20.95	23.78	22.35	23.19	23.00	20.95
A_{18}	m^2	750	23.24	23.34	21.41	23.86	21.85	21.32	24.63	21.88	22.87
A_{19}	m^2	635	31.39	32.96	31.66	29.76	30.56	32.36	28.90	29.47	33.33
A_{20}	m^2	400	35.64	36.75	37.55	36.58	39.03	35.38	37.56	35.40	36.21
A_{21}	m^2	348	38.05	39.78	38.77	39.28	35.44	35.79	39.19	39.63	35.08
A_{22}	m^2	250	50.16	50.34	49.73	52.14	45.85	52.27	49.12	50.30	49.46
A_{23}	m^2	100	26.56	26.26	27.36	26.88	25.07	24.98	27.50	24.59	27.82

Table 2 (cont'd). Input data for illustrative example.

Act. ID	**Unit**	**Quantity**	**Unit Prices (TL – Turkish Liras)**								
			O	**B_1**	**B_2**	**B_3**	**B_4**	**B_5**	**B_6**	**B_7**	**B_8**
A_{24}	m^2	150	35.63	36.26	34.12	37.72	34.84	35.66	35.98	32.82	35.03
A_{25}	m^2	75	23.61	24.87	21.25	21.81	24.29	23.15	23.41	24.72	24.89
A_{26}	m^2	98	28.59	25.89	26.65	28.53	28.52	31.41	28.69	28.21	30.46
A_{27}	m^2	50	27.29	27.41	25.95	29.84	26.82	28.77	25.32	25.65	24.73
A_{28}	m^2	43	29.98	30.20	29.84	27.50	30.75	28.48	32.57	28.26	30.09
A_{29}	m^2	66	44.61	45.92	47.46	44.67	40.65	48.92	42.76	43.53	41.53
A_{30}	m^2	40	58.94	54.01	56.03	53.11	59.19	59.65	54.99	59.98	60.40
A_{31}	m^2	40	39.54	43.20	42.80	39.07	37.86	38.69	42.66	41.16	39.66
A_{32}	m^2	100	40.24	42.55	39.59	41.02	42.52	43.04	41.36	41.56	36.69
A_{33}	m^2	450	1.94	1.75	2.08	2.01	1.94	2.00	1.99	2.01	1.75
A_{34}	m^2	350	2.35	2.17	2.48	2.39	2.27	2.55	2.20	2.58	2.19
A_{35}	m^2	40	16.91	15.70	15.29	15.72	16.19	15.85	15.66	16.05	17.10
A_{36}	m^2	60	20.71	18.91	20.89	20.97	20.51	21.01	22.31	20.95	20.96
A_{37}	m^2	50	14.68	15.50	14.91	13.82	13.55	13.29	14.37	14.57	13.84
A_{38}	m^2	1000	27.71	26.86	27.56	26.32	29.55	26.55	26.78	27.64	28.43
A_{39}	m^2	450	43.24	39.04	46.78	45.19	46.00	43.59	45.01	45.12	47.13
A_{40}	m^2	900	32.39	34.31	29.90	34.25	33.58	32.77	29.28	31.71	29.34
A_{41}	m^2	650	33.90	33.90	30.71	36.87	36.48	30.83	35.46	31.94	31.03
A_{42}	m^2	100	6.29	6.84	5.71	6.33	5.92	5.68	5.97	6.86	6.02
A_{43}	m^2	1000	1.29	1.29	1.31	1.23	1.40	1.36	1.22	1.19	1.18
A_{44}	m^2	150	7.33	7.01	6.67	6.64	7.45	7.91	7.12	7.29	7.64
A_{45}	m^2	2000	11.78	11.58	12.45	11.39	11.86	12.38	11.66	12.90	12.94
A_{46}	m^2	1600	30.04	29.74	30.87	31.84	27.61	30.66	31.46	29.77	30.38
A_{47}	m^2	2000	29.56	30.55	30.33	30.01	32.43	28.17	30.23	29.49	27.07
A_{48}	m^3	600	4.59	4.65	4.72	4.72	4.68	4.50	4.27	4.87	4.15
A_{49}	m^3	450	5.84	5.36	6.42	5.29	5.88	6.11	5.41	6.06	5.64
A_{50}	m^2	750	4.83	5.29	4.61	4.97	5.18	4.77	4.79	4.86	5.21
A_{51}	m^2	1600	115.81	107.85	117.90	125.97	116.49	107.78	122.21	120.78	120.28
A_{52}	m^2	650	136.51	142.73	139.82	133.89	126.59	128.11	149.12	141.47	126.39
A_{53}	m^2	650	88.36	89.02	81.44	91.52	92.22	93.89	89.25	79.90	81.71
A_{54}	m^2	250	123.24	133.28	134.02	112.88	133.04	134.99	119.83	131.82	114.27
A_{55}	m^2	690	50.34	48.72	47.31	53.42	49.00	46.54	53.07	51.53	45.89
A_{56}	m^2	600	170.88	157.50	161.31	160.47	179.91	166.13	182.67	164.95	182.67
A_{57}	m^2	350	319.38	338.86	338.76	344.12	339.48	325.54	350.95	306.97	302.08
A_{58}	m^2	400	250.09	261.30	253.70	264.69	249.89	244.55	265.10	264.46	226.00
A_{59}	ton	1300	2096.56	2127.33	2152.31	1941.54	2089.57	2077.30	2026.49	1988.62	2045.57
A_{60}	ton	1650	2017.94	2140.37	2143.31	1877.71	1975.24	1998.95	1887.98	2160.53	1974.92
A_{61}	ton	350	1972.66	1871.37	1796.76	2120.92	2169.36	1789.12	2155.85	1837.37	1987.05
A_{62}	ton	1000	1939.23	1985.11	1832.36	1762.37	1999.50	2115.62	2044.00	1860.08	1918.36
A_{63}	ton	1150	1914.79	1914.13	1780.31	2038.14	1781.33	1987.31	1875.30	1810.11	1885.75
A_{64}	ton	200	3386.01	3642.50	3635.81	3425.98	3236.22	3658.23	3346.48	3591.23	3238.26
A_{6}	kg	4000	8.64	9.39	8.07	8.58	7.87	8.65	9.13	8.38	7.97
A_{66}	m^2	2000	9.59	9.16	10.29	10.06	9.74	10.16	9.55	8.82	10.51
A_{67}	m^2	600	13.00	12.96	13.32	14.30	14.00	13.68	11.84	12.36	14.07
A_{68}	m^2	150	5.23	5.62	5.34	5.53	5.32	5.06	4.91	5.17	5.45
A_{69}	m^2	2000	15.65	14.26	16.26	14.72	16.25	15.96	14.87	15.75	16.47
A_{70}	m^2	2000	18.56	19.20	16.81	18.13	19.78	18.95	17.37	17.73	18.78
A_{71}	m^2	700	28.60	27.78	27.36	26.28	31.23	30.24	27.97	27.13	28.49
A_{72}	m^2	2000	20.88	21.98	22.75	22.95	19.38	19.91	21.36	19.67	22.51

The construction cost (*ECC*) estimated by the owner is 13,766,619.41 TL, and the bid prices offered by 8 bidders are 14,043,276.86 TL (BP_1), 13,826,569.14 TL (BP_2), 13,389,997.59 TL (BP_3), 13,624,850.19 TL (BP_4), 13,947,114.50 TL (BP_5), 13,622,893.85 TL (BP_6), 13,641,083.17 TL (BP_7), and 13,538,572.61 TL (BP_8), respectively. The weights assigned to grading systems are different from the weights used in Polat et al.'s (2018) study due to the addition of three new grading systems to the proposed model. In this study, weights were assigned as 15% for first grading system, 10% for the second one, 5% for the third one, 10% for the fourth one, 30% for the fifth one, 5% for the sixth one, 5% for the seventh one, and 5% for the eighth one. The owner can assign weights to each grading system according to the project characteristics. The ranking of the bidders according to the final scores is presented in Table 3. Based on the results presented in Table 3, Bidder 2 (B_2) has the highest final score, whereas Bidder 1 (B_1) has the lowest final score. Although B_3 offered the lowest bid price, it is ranked sixth according to the final scores. Moreover, B_1 has the lowest final score while offering the highest bid price. Finally, B_1 submits the highest bid price and the most unbalanced bid, whereas B_2 submits the most balanced bid despite not offering the lowest bid price. In other words, B_2 is the most appropriate bidder for the owner. The findings of this study reveal that the improved model provided a different ranking of bidders than the one obtained by Polat et al.'s (2018) model.

Table 3. Rankings of the bidders.

Proposed Models \ Bidders	B_1	B_2	B_3	B_4	B_5	B_6	B_7	B_8
Previous unbalanced bid detection model *	6	2	8	3	7	4	5	1
Improved unbalanced bid detection model	8	1	6	4	7	3	5	2

* The model developed by Polat et al., (2018).

4. Conclusion

The main aim of this study is to propose an improved version of the unbalanced bid detection model developed by Polat et al. (2018). The proposed model uses eight different grading systems. Owners may assign weights to each grading system according to the characteristics of their projects. After assigning weights to each grading system, the final scores of bidders can be calculated. All bidders can be evaluated not only according to the offered bid prices but also according to the calculated final scores. An illustrative example is presented to validate the applicability of the proposed model. It was observed that the improved model detected the unbalanced bid but provided a different ranking of bidders than the one obtained by Polat et al.'s (2018) model. However, this study is limited as it only focuses on unbalanced bids created by quantity error exploitation method in unit price contracts. In future studies, the model can be developed so that it can deal with the detection of unbalanced bids created by different methods.

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Industrialized and project-based construction - Standards versus business models

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Abstract

Digitalization transforms the design, construction and operation of buildings and brings promises of integrated information exchange, ease of communication and productivity improvements for the whole construction sector. These promises depend significantly on the establishment of common information standards, i.e. rules and classification of information. However, despite rigorous efforts on development of standards and considerable technology advancements, standards are not yet fully adopted in construction and benefits from digitalization are not fully capitalized. The objective of this study is to review the adoption of standards and business model renewal for industrialized suppliers of precast concrete elements, with the purpose of reaching enhanced understanding of the mechanisms of standards adoption and business model renewal. The study identifies driving forces for adoption of standards that counteract with arguments for business renewal, explained in terms of a market versus a hierarchy approach in this context. The market approach promotes adoption of open standards for enhanced competition, ease of communication and information exchange as well as improved utilization of industrialized construction. The existing lack of common standards for precast elements, identified in this study, render e.g. waste due to structural re-design and liability uncertainties. However, on a market with open standards, the precast suppliers find it difficult to fully utilize and benefit from their existing operational platforms. Precast supplier search for adoption of the whole value chain of precast structural frameworks, i.e. a hierarchy approach, to protect their market position and maintain their business offerings of complete structural frameworks that include design, manufacturing, logistical services as well as on-site assembly. The integrated hierarchy approach concurs with arguments for industrialized construction, i.e. collecting experiences from design, manufacturing, logistics and assembly as a basis for continuous improvements. The study thus contributes to the understanding of drivers and impediments for adoption of standards versus business renewal in construction.

Keywords: Industrialized construction, information standards; business model; precast element; product service system

1. Introduction

A strong driver for digitalization in construction is the request for continuous and integrated information exchange between all actors of the construction process [1, 2], but the potential of integrated and digital communication and information exchange in construction depend significantly on the establishment of common information standards [3], file formats and, business models [4].

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There are numerous examples of national and international classification systems developed to support the increasing digitalization in construction. CoClass is one example of a new Swedish classification system designed to improve information management in the construction and asset management sector [5]. Similar classification systems are e.g. the Danish Cuneco Classification System [6], the OmniClass [7], created and used by the North American architectural, engineering and construction industry (AEC) and the Uniclass, that supports the construction sectors of the UK.

The civil infrastructure sector demonstrates an example of the need of open standards due to digitalization in the development project called "The Virtual Construction for Roads". In the real estate sector, five Swedish public construction client organizations have taken a similar initiative with the purpose of developing open standards to facilitate systematic use of BIM in building projects and real estate management [2]. Within land surveying there is a standard data model and exchange format called CityGML that enables common 3D urban objects of cities and landscapes, such as buildings, roads, rivers, bridges and vegetation, to be shared and exchanged between applications. The establishment of COBie, Construction Operations Building Information Exchange, provides an example of a standard data spreadsheet format that facilitates information deliveries from BIM systems to Computer Aided Facility Management (CAFM) systems for facility's operation and maintenance (FM) [8]. BuildingSMART [9] has developed bsDD, the buildingSMART data dictionary, which constitutes an open and international standard library of construction concepts and their attributes [10].

Thus, there are several examples of local, national and international standard classification systems that share the same fundamental idea of facilitating integrated information flow between systems and actors of the construction process. Such an integrated information infrastructure reaches beyond the architectural, engineering and construction (AEC) industry, and includes urban planning, civil infrastructure, real estate management, building material manufacturing, industrialized construction and other aspects of the construction sector.

1.1. Problem statement

Despite rigorous efforts on development of information standards and considerable advancements in technology, standards have not yet been fully adopted and benefits from digitalization have not been fully capitalized upon by industry stakeholders [11]. Research report on a number of impediments for the implementation of digital solutions and adoption of standards in construction, e.g. with references to business risks and challenges related to the implementation of new technology and work processes [12], commercial and legal barriers [13] and, requirements for legal governance and contractual systems [14, 15]. Accordingly, construction digitalization and adoption to new standard systems provide thorough change processes for all stakeholders that need to reconsider their business models, protect and/or reconfigure their commercial offers and balance the risk distribution with their customers and suppliers in order to develop their competitive advantage and maintain their revenue [16].

1.2. Purpose, objectives and delimitations

The objective of this study is to identify and review adoption of standards and business model renewal for industrialized suppliers of precast concrete elements with the purpose of bringing light on the driving mechanisms for adoption of standards versus business model renewal. The study operates in the interrelation between industrialized and project-based construction. The industrial suppliers of precast concrete elements, in this study referred to as precast suppliers, are geographically limited to the Swedish construction market.

2. Method

The study rests upon eleven semi-structured interviews with key representatives from eight different companies and one trade association. All interviews were recorded and transcribed and the transcriptions were sent back after transcription to the respective respondents for proofreading and eventual corrections in the documentation.

Abetong AB [17], a precast supplier, StruSoft AB [18], an engineering software provider for the precast building industry and Tyréns [19], a community development consultancy, represented the industrialized side of construction. One precast supplier wanted to stay anonymous. The project-based side of construction was represented by IKANO Bostad [20], Veidekke Bostad [21] and NCC [22], contractors and property developers and, Akademiska Hus [23], a Swedish state-owned property company and The Association of Swedish Building Materials Merchants [24].

3. The business model framework of precast suppliers

The review of business models and information standards among precast suppliers in this study has its starting point in the business model framework for industrial house-building companies presented by [25]. This business model consists of the operational platform, the market position and, the offering (see figure 1).

3.1. The operational platform

The operational platform describes the precast suppliers' internal structure of resources, competencies and production facilities, but it also includes activities and operations such as management, planning, design, supply chain and information and communication systems [26, 27].

All the precast suppliers in this study have made considerable investments in sophisticated industrial production facilities, capable of producing all kinds of precast elements. The operational platforms also includes sophisticated services in terms of customisation of elements, structural design of building systems, planning and logistical services as well as clash detection and coordination with MEP-suppliers.

3.2. The offering

The offering represents the products and services provided by the precast suppliers. There are two distinct types of offers identified among the precast suppliers. The first is the traditional offer of precast elements such as concrete pillars, columns, stairs, walls and slabs. The other type of offering includes the whole concept of structural design, manufacturing, logistical services and assembly of complete precast concrete structural frameworks for whole buildings. This offering is an example of complex structural concrete frameworks composed by a number of standardized and well-documented building elements of precast concrete slabs, walls, pillars and beams. Offerings that systematically combine both tangible products and intangible services are commonly referred to as product service systems, PSS [28, 29]. This study will refer to the precast suppliers' offerings of complete precast structural frameworks as PSS-offerings.

3.3. The Market position

The market position of the business model framework describes how the precast suppliers' relate to their customers on the market. The precast suppliers in this study operate in two principal lines of business. The offering of standard precast elements represents the traditional line of business in which the precast suppliers act solely in the role of a manufacturer of building elements.

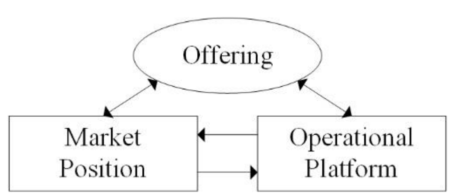

Fig. 1. The business model framework used as the basis of analysis in this study [25]

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The other line of business represents the PSS-offerings of complete precast structural frameworks and additional services. In this line of business, the precast supplier operates as a contractor with full responsibility for the design and construction of the structural framework. Accordingly, the precast supplier acts on behalf of the building client, cooperates with the design team, operates side by side with the general contractor and are directly involved in the design and onsite building production.

4. Standards versus business models

4.1. Standards for precast concrete elements

The precast suppliers in produce more or less the same set of products. However, despite of the almost identical range of products there is no common standard for classification of the various precast elements and their properties. Instead, all precast suppliers have developed their own company specific classification systems (see table 1).

Table 1: Examples of precast suppliers' naming of the different types of concrete elements

Product	Supplier A	Supplier B	Supplier C
Wall (solid)	V	RV	V
Wall (sandwich)	RW	RW	W
Pillar (circular)	P or OP	OP	P
Pillar (rectangular)	P or RP	RP	P

The lack of common standards impedes the precast suppliers' communication and information exchange with their client or members of the design team. Besides, it prevents integration between structural design of precast and in-situ frameworks and renders numerous situations of rework, i.e. waste, when a structural design solution for in-situ production needs translation into a corresponding solution for precast manufacturing [30].

Finland and Norway show a different situation about national standards for the design of structural frameworks. The Finish BES system represents a specific standard system for precast elements that builds upon standard modular dimensions for slabs, interior and external walls, bathrooms, staircases and other precast elements of standard dimensions [31]. Corresponding standard systems for industrialized construction is prevalent in Norway [11].

Despite the obvious advantages of open standards for precast structural frameworks, the Swedish precast suppliers express hesitation about adoption of open standards. Any structural engineer can execute structural design for precast elements based on open standards and the situation is the same for logistical services and assembly of precast elements on site. Consequently, open standards for precast elements will challenge the market for PSS-offerings and reduced the precast suppliers´ to mere manufacturers of precast elements.

4.2. Business models for precast suppliers

The precast suppliers require early involvement in the project process in order to harvest the full business potential of their PSS-offerings. Too late involvement will lead to unnecessary waist in terms of re-design of the structural framework and will render uncertainties about responsibilities for the structural design. The precast suppliers get involved early in a project e.g. when hired directly by the building client, which can be the case in separated coalitions.

Early involvement can also be the case when the main contractor in an integrated project coalition procures the precast supplier. However, the contractors' decision about whether to choose a precast or a traditional in-situ structural framework are sometimes a concern of the construction managers on site rather than the technical engineers in the design phase. Consequently, decisions about applying precast suppliers are sometimes taken late even in integrated project coalitions.

The given situation, with two parallel design solutions, raises important questions and uncertainties about responsibilities between the original team of the architectural and structural design and the structural designer of the precast structural framework [30].

5. Conclusions

This study, operating in the business interface between industrialized and project based construction, identifies driving forces for the adoption of standards from a market perspective that counteracts with the precast suppliers' arguments for market protection. Incentives for adoption of standards as well as renewed business models provide an example of a power balance between market and hierarchy (see e.g. [32]).

The market approach promotes adoption of open standards for the prefabrication industry, as in Finland. This approach will open up the market and making it possible for different actors using the same set of common standards to perform their respective part of the value chain of precast elements. For example, one actor can do the structural design while another actor do the manufacturing of precast element and a third performs the logistical service as well as the assembly of the precast elements on site. Open standards thus promote increased competition, supports information exchange and prevents the identified problems design rework when shifting from in-situ to precast structural frameworks. The market approach, however, implies a product focus where the market position of the precast supplier is reduced to a mere manufacturer of precast concrete. Competition is based on lowest price for standard elements of low complexity and business relations are described by delimited and project-based contracts, see figure 2.

With open standards, the precast suppliers cannot fully utilize and benefit from their existing operational platforms with e.g. qualified structural design competences, logistical services and resources for onsite assembly. The reserved attitude to adoption of standards among precast suppliers identified in this study, concur with Koch [3], who found that actors on markets with no a legal demands for the use of standards will only consider adoption of standards if it generates immediate benefits for the business.

In the hierarchy approach, the precast suppliers try to align the whole value chain of precast structural frameworks in order to provide PSS-offerings and to secure the most efficient use of their operational platforms. As a supplier of PSS-offerings, precast suppliers act as turnkey contractors responsible for the design, manufacturing, deliverance as well as assembly of the precast structural framework. This integrated work process provides opportunities for the precast supplier to gather experiences from the design, manufacturing, logistics and assembly of the precast elements as a basis for continuous improvements. The hierarchy approach enables early involvement, shared risk and rewards and, close collaboration with the design team as well as other contractors. Besides, business relations rely on trust rather than strict contractual agreements, the product is unique and complex and competition is a matter of capabilities and qualities of the expected results. Accordingly, precast suppliers promote their PSS-offers as a way to climb the value chain and get more closely involved in the project-based construction.

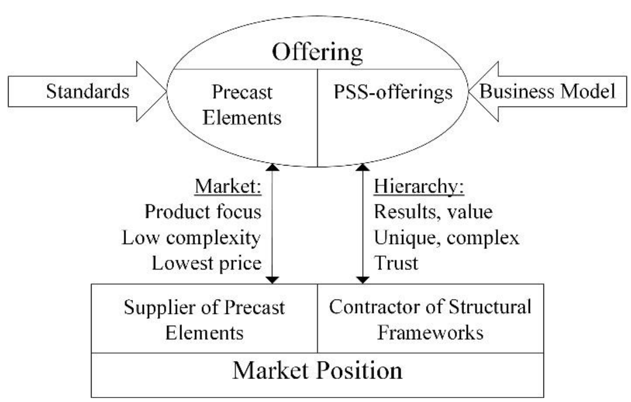

Fig. 2. Implications of standards and business models on offerings and market position

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Industry 4.0 and construction supply chain management

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Abstract

Industry 4.0 has contributed positively to establishing digital value-added supply chains to enable information flow between environment, clients, business partners and products. The aim of this article is to present a review on the features, elements and role of industry 4.0 to construction firms supply chain management. This article further reiterates the importance of digital industry 4.0 in construction firms supply chain management, especially on how construction industries and stake holders can reduce project delivery time, material and labor costs. The article reveals that industry 4.0 will have a high significant effect on the future of construction supply chain if it can identify crucial elements for improvement, such as speed, adjustability, measure of productivity, and high-test quality. The article also suggests further comprehensive research on how technological advancement can bring global competitiveness of the construction industry supply chain.

Keywords: Supply Chain Management; Construction; Industry 4.0; Global Competitiveness; Information Flow.

1. Introduction

The construction supply chain management is a technique applied in achieving integration between the several elements of the construction chain such as vendors, contractors, designers, clients, and direct suppliers (Papadopoulos et al., 2016). Construction supply Chain management helps to balance the information, cash, and material flows among set of construction companies to create value for their internal and external buyer (Xue et al, 2007). More specifically, the definitive characteristic of supply chain in construction means the total participating companies have dissimilar range, of both substantial and cognitive functioning, to the point of manufacturing. However, the planning of various materials to the position where different commodities meet is hindered by both substantial and cognitive distances (Dainty et al., 2001; O'Brien et al., 2008). This means identification of different characteristic that are novel to construction supply chain or construction projects will require some specific management effort such as strategy to build long time construction industry evolution and capabilities. Over the years, poor information flow between general contractors and subcontractors has contributed to current challenges

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been experienced in construction industry such as increase in lead times of equipment and materials delivery to the site, inefficiencies in demand, and lack of involvement problem solving. Owning to these challenges, construction firms and suppliers have emerged to take actions such as improving organizational participation among players in the construction chain and introduction of industry 4.0 routines, processes and operations to construction supply chain management. Although, construction industry experiences a distinct challenge than the manufacturing industry such as complicated interrelated processes occurring at locations and different stages of construction. Industry 4.0 has contributed positively to establishing digital value added supply chains to enable information flow between environment, clients, business partners and products through the automation of producing environment (kagermann et al., 2013; Dallasega, 2018). In today's global environment, information and data management is a meaningful intermediary in industry 4.0, it is done with the aid of cloud to collect, appraise and evaluate data efficiently, faster machine operations to manufacture quality goods at a less costs, boost productivity, and competitiveness in construction companies. Industry 4.0 impact to construction industry current forecast growth is reported by Construction Products Association (2016), which reveals that United Kingdom construction product sector is likely to reach its maximum output by 2019 and can grow over £30 billion by 2025 with cheaper & timely deliveries of buildings because of the integration of automation, digitalization, industry 4.0, and building information modelling through supply chain management and direct United Kingdom construction economy. It is advisable that every firm must introduce swift digitalization, effective and agile internet of things, and large data evaluation to its processes because it decreases human factor in their activities (Li and Yang, 2017). It is a processes or technique which construction industry must be built upon in order to achieve intelligent systems, resource efficient direct economy and efficient products.

The aim of this article is to present a review on the features and role of industry 4.0 to construction firms supply chain management. Section two of the article identifies the interfaces of distinct functions that continue at the center of construction supply chain and four roles of supply chain in construction management. Section three discusses the headway in technology that comprises the establishment for Industry 4.0. Section four of the article discuss the policy framework of supply chain and the features of industry 4.0. Finally, a conclusion section.

2. Supply chain management and construction industry

The construction supply chain management is described as the collaboration of key determinant process in the construction supply chain and incorporation of major players involved in construction chain such as designers, clients, suppliers, and contractors (Xue et al., 2005). The key objective of construction supply chain is to improve construction performance, direct precise quantities of raw materials to the site, and improve client value while minimizing cost attributed to production, inventory and transportation. This means the Integration of digitalization and prefabrication method in transporting materials from construction site to the operation environment will improve quality, time and reduce cost. Although, the construction supply chain method is distinct from manufacturing operations in industries, supply chain management method can still be applicable in construction industry. The disruption in the construction operations is caused by failure in collaboration with its value supply chain which makes supply chain method a difficult task to attain among suppliers, designers, contractors, and clients (Christopher and Peck, 2004). The assembly and transportation of all type of materials to the site involves dissimilar supply chain framework with distinct time must be viewed. The designed supply chain framework includes; a) Engineer- to-Order b) Make-to-Order c) Make-to-Stock and d) Assemble-to-Order (Dallasega and Rauch, 2017; Dike and Kapogiannis et al., 2014).

Vrijhoef et al., (2001) and Akintoye et al., (2000) have identified some interfaces that are present within the conversion process and the construction supply chain. Table 1 highlighted the different interface and problem description that exists within the construction supply chain.

Table 1. Summary of some general problems that exists within the construction supply chain

Interfaces	Problem Description
Feed and Engineering Interface	Inaccurate certification, Design alteration, Wrong calculations, Prolong time for design revision and approval
Client Feed	Extended time for Design Changes and approval, No constructability
Engineering Procurement, Vendors Interface	Incorrect data, Engineering designs not applicable for use
Engineering Site Interface	Engineering personnel not present on site for the field engineering
Project Completion and Commissioning	Complicated completion due to security concerns, Problems with residents.
Procurement and Logistics Interface	Lack of inaccurate logistic studies, ineffective logistics routes, permits & licenses required, and customs clearance setback.
Logistics and construction Site	Big shipments, Lack of acceptable packing, bad weather or Political conditions, extended storage time
Major Contractor Subcontractors	Wrong and defective deliveries, Large shipments, Long storage period, Interfaces with several subcontractors and suppliers, Poor training of contractor's suppliers
Suppliers and Subcontractors / Site Interface	Wrong and defective deliveries, Extended storage time, Contract planning, less productivity of many subcontractors, Poor training of personnel
Commissioning and Operation Interface	Unresolved quality and technical problems, Delayed operational time due to late completion

Source: Akintoye et al., (2000), authors' own editing.

Vrijhoef and Koskela (2001) reiterated the four roles of supply chain management which is concurrently applied by major contractors to maximize efficiency in construction management of construction site. The mentioned four vital roles of supply chain in construction are shown in figure 1.

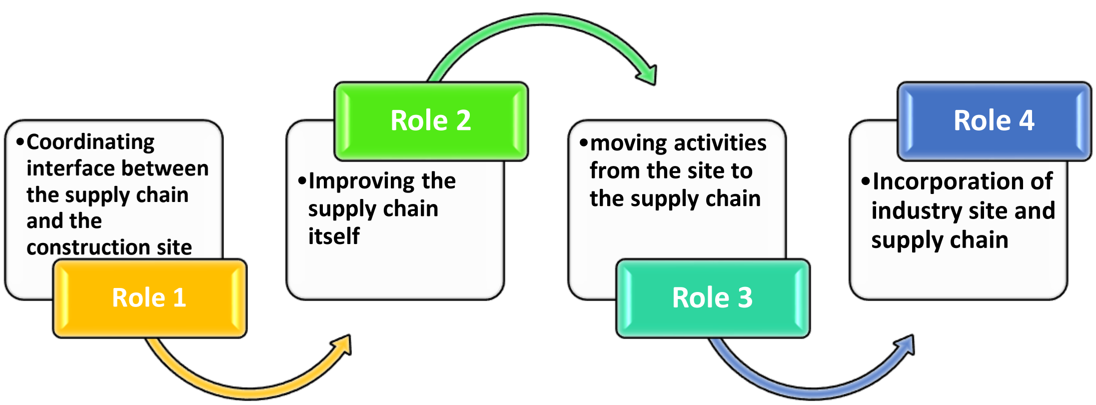

Figure 1: The four vital roles of supply chain management in construction, Source: Vrijhoef and Koskela (2001), authors' own editing.

From figure 1, the activities in role 1 implies that the contractor goal is on how to improve the material flow, labour flow, minimise duration of construction site activities, and reduce costs. This target may be achieved by coordinating the interrelation between the suppliers in the supply chain and construction site. Role 2 reveals that detailed material cost and analysis of time are crucial for distinguishing potentials in developing construction supply chains. Therefore, activities relating to storing of material or inventory and logistics cost may be directed to the supply chain itself with the aim of achieving quality in design at a reduce costs. The aim in Role 3 is on how direct suppliers or

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contractors can minimize the total costs and time of construction, it is done by transferring the activities from the construction site to the first point of value supply chain. Another way of minimizing the total costs and total time of construction is the Prefabrication technique which cancels almost all site activities from the manufacturing chain. Lastly, the goal in role 4 is finding new replacement for the incorporation of the site and the supply chain. The Clients, general and sub-contractors may focus on the incorporation of management, site manufacturing and enhancement of the construction supply chain since site manufacturing is entailed in supply chain management.

3. Industry 4.0 concepts

Industry 4.0 means the technique of increasing automation of the production space and value-added supply chain through interaction between clients, their location, and products. It can be referred to as an event that penetrates the entire value chain of an organisation through technological activities, increases clarity of procedures by making use of digitization, and finally incorporating value added chain into customer supply chain. It is a concept which started in the manufacturing sector but gradually transforming the construction industry through digitized means (kagermann et al., 2013; lasi et al., 2014). It is an elaborate strategy which was initiated by German government in association between industrial and manufacturing organisations with the aim of encouraging industrial modification and obtainment of a leadership role in today's global competitive producing sector (Bartodziej, 2017). In today's manufacturing environment, end consumers can choose from a variety of products, but they seem not to be satisfied with the value. Therefore, manufacturers are in a race to create personalized products while retaining value, customers, and surviving the worlds competitive market (Prahalad, 2004). industry 4.0 usefulness is the ability to link all scenarios involved in value added supply chain such as people, systems, relevant information in real time, and data of value-added flow across computers. The collection and analysis of information involves application of computerised technologies and strategy in linking the manufacturing and logistics value chain (Cappellin et al., 2017). It means the development of interconnected systems that allows large data collection within each other communication devices through the application of Internet of Things are the most characteristic of industrial revolution. According to Qin et al., (2016), the industry 4.0 agenda relies on the following factors; a) smart products capable of collecting and transmitting data to the central system with the aid of processors and sensors b) business activity that relies on the combination of information flow between manufacturers supply chain and trade-off real time data c) smart factory that form part of replacing real time data in a conditioned manner and the manufacturing activities are self-dependent d) consumers may order commodity with any function and redesign their order at any period of the manufacturing process.

According to rubmann et al., (2015), the enabling technologies that forms the foundation of industry 4.0 are characterized by remote, enhanced branches that combines together as a fully integrated, computerised, and enhanced manufacturing flow thereby leading to greater capability and connection between supply chain. Figure 2 shows nine foundational technology advancement of Industry 4.0

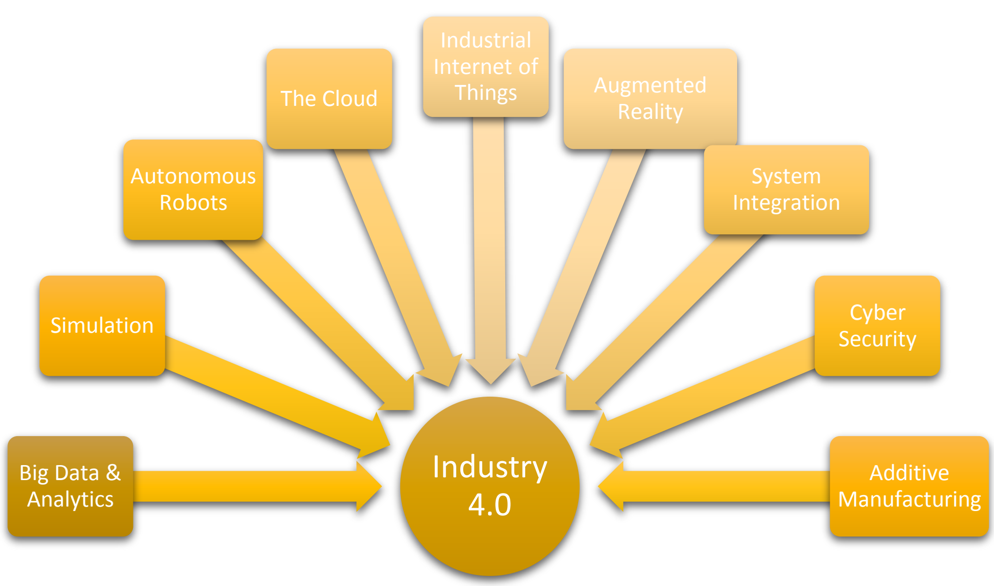

Figure 2: Nine foundational technology advances of industry 4.0, Source: Rubmann et al., (2015), authors' own editing.

Figure 2 shows that industry 4.0 can be transformed if only the sensors and ICT tools are connected along the value-added chain beyond one industry. The connected sensors and IT systems are called cyberphysical systems because they interact and configure one another using approved internet-based protocols. Therefore, the functions of nine pillars of technological advances that form the core process for industry 4.0 in Figure 2 are; a) Augmented Reality: it comprises of devices that allows real time data to improve decision process and job procedures b) Additive Manufacturing: it allows firms in manufacturing specimens and completed products directly on the supply chain with a less transport distances through decentralized manufacturing systems c) Simulations: it allows the controller to perform test experiment and optimize the device functions for the next merchandise in line thereby reducing cost and machine set up time d) System Integration: it allocates personnels with real time data to correct defective work procedures throughout the entire supply chain e) Cybersecurity: protects the computer systems, industrial systems, and manufacturing lines ensuring a network security f) Big Data: it optimizes and analyse huge volume of data to enhance products quality and energy saving g) The cloud: large amounts of device data and connection will be made available by the cloud system and accessibility of production services at all times h) The Industrial Internet of Things: allows field devices and set of technologies to communicate, interact between artificial world and people, and with more centralized systems i) Autonomous robots: it performs different complex assignments which costs less than the robots used in today's manufacturing.

4. Industry 4.0 and construction industry

The construction industry experiences a high level of uncertainty and distinct constraint than the manufacturing industry to maximize productivity such as large volume of connected processes, and partaking players at different stages and in different site make the construction firms process challenging (arayici and coates, 2012). Construction sites are usually faced with obstacles in production processes, high variability, missing materials, handling of material, and unpredictability which makes linking of supply chains to the construction progress difficult. Therefore, industry 4.0 concepts, embedded systems, cloud computing, additive manufacturing, augmented reality, Product-Lifecycle-Management, information technologies, and big data is vital in overcoming the individual challenges in construction supply chain deficiences (Li and Yang, 2017). The building information management technology is important in the pre-construction phase because it combines with the location base service to track material. Another means of improving construction industry supply chain process is by simulating site management process in a virtual construction site to see if it can effectively monitor workers, tools, materials, and equipment. According to oesterreich and teuteberg (2016), the concepts of industry 4.0 is important in digital supply chains of the construction industry because it enables interaction and communication between clients, project managers, business partners, and construction sites. The policy framework of supply chain and its industrial competitiveness on the global market relies on the features of industry 4.0 (Nowotarski and Paslawski, 2017). Table 2 gives the functions and industry 4.0 key features.

Table 2: Function and industry 4.0 key features

Features of Industry 4.0	Functions
Interoperability	Incorporation of people and smart factories to transmit with each other
Virtualization	A virtual copy of the smart factory is established by connecting sensor data with virtual plant specimen and simulation specimen
Decentralization	capability of cyber-physical components to make instruction of its own and manufacture it domestically
Real-Time Capability	the ability to collect and appraise real time data and evaluate the results.
Modularity	Adjustable properties of smart factories to replace or expand its individual modules.

Source: Nowotarski and Paslawski (2017), authors' own editing..

From Table 2, features of industry 4.0 such as decentralization, virtualization, real-time competency, modularity, and Interoperability can be useful to construction firms through the application of work flows in reducing material and labor costs, less in project delivery time and materials reduction through prefabrication of parts and additive manufacturing method. According to Ortiz (2009), the digitization of industry 4.0 in the construction chain is placed across departments and individual divisions which covers information gathering, evaluation of current data state of each value chain interaction, Integration of humans and smart production site to communicate with each other, and generate autonomous technologies.

The industrial revolution 4.0 will have a positive effect on future of construction supply chain since it comprises of three points growth (alaloul, 2018). The three points growth includes; a) Digitization of manufacturing: data blue print for organization and construction development, b) Automation: design for information sourcing from the construction site and other machines operation, and c) connecting construction sites to a supply chain: fully conditioned data exchange.

Manufacturing firms will adopt Industry 4.0 at different stage and in distinct ways such that organizations with a top level of article variants will take advantage from a greater degree of changeable process that can create productivity gains and reduce error rate (Rüßmann, et al., 2015). The set priorities among production processes and industry 4.0 are as follows:

- Finding crucial areas for amendment such as speed, adjustability, measure of productivity, and high-test quality. Followed by, examining how nine foundational technology advancement of industry will bring improvement in the assigned areas.

- Study the lengthy impact on the staff and plan vital staff planning. Then readjust roles, recruiting, and technical training to equip the staff with comprehensive IT skills.

- Manufacturers and suppliers must try to customize infrastructure and knowledge as they involve the Industry 4.0 technologies

- System suppliers must assemble a scenario-based vision of the long-term industry goals and ensure that their design will equip them for the most likely scenarios.

- Suppliers need to understand how they can introduce Industry 4.0 technologies in order to offer the best benefits to their customers.

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CONCLUSION

Industry 4.0 is a means of increasing computerization of the construction industry and digital value-added supply chain to enable interaction between clients, their environment and products. Over the years, lack of information flow between general contractors and subcontractors has contributed to current challenges been experienced in construction industry such as increase in lead times of equipment and materials delivery to the site. Therefore, this study proposes the adoption of technologies to secure constant information flows to the construction site to avoid disturbance to the workflow. It also important for contractors to focus on forming relationship among players in the construction chain, processes, operations, and direct suppliers. Lastly, in order for future development of industry 4.0 in construction supply chain management, producers, suppliers, organizations, businesses and government must work together to integrate framework and education as they adopt industry 4.0 tools.

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Methodology of real estate valuation in a whole life cycle context

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Abstract

Valuations of real estate are widely used in financial and other markets. Valuation methodology is based on the workings of a free market economy. The value can be determined by a single valuation approach or by a combination of multiple approaches. In real estate valuation it is essential to understand the modelling of the economic potential of the property during the life cycle. The combination of theoretical knowledge with valuation practice has been implemented through cooperation with an international audit and consulting company operating on the Czech market. The aim of the project is to describe the life cycle of real estate from the point of view of the appraiser and identify the key assumption affecting the valuation methodology used for real estate valuation.
The outcome of the project could be used by real estate valuation experts as a guideline for choosing the appropriate valuation approach.

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Keywords: Real estate valuation; Life cycle; Valuation methodology; Change in value; Development property valuation

1. Introduction

During the life cycle of the property there are significant changes in key assumptions which cause a change in the valuation methodology. The valuation standards must be adapted to global conditions, and due to this fact, are usually very general. Property valuation is a subjective matter. Each appraiser may have a different opinion and may use different valuation approach for the property valuation. At present, market value price is mostly valuated by comparison with other similar buildings, cost and yield analysis of the real estate. [1]

According to the International valuation standards [2] there are three basic and generally accepted valuation approaches used for the valuation of real estate; the market (comparative) approach, the income approach and the cost approach. The use of single basic valuation approaches is particularly appropriate for objects that are in accordance with their best and highest use, generating adequate returns or are commonly traded on the market. For the valuation of development property where work on improvements has commenced but is incomplete, the application of single valuation approaches is not sufficient. For the property valuation under construction or refurbishment the residual method is generally used.

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One of the most common differences in values between two independent appraisers is caused by the different assessment of key assumptions determining the valuation methodology. The land for construction can mentioned as an example. One appraiser can take into account comparable transactions in the locality and apply for the valuation comparative approach. Another appraiser may see stronger development potential and apply the residual method. Although both appraisers proceeded in accordance with the appropriate valuation standard the difference in values between these valuation methods could be significant. This paper should summarize the best market practice used for the selection of the appropriate valuation methodology.

2. Valuation approaches

According to IVS 400 Real Property Interest [2] the three basic valuation approaches can be applied for real estate valuation and all of them are based on market principles.

- Market approach – The market approach provides an indication of value by comparing the asset with identical or comparable asset for which price information is available [2]. The principle of comparison is based on the economic concept of substitution that a knowledgeable and prudent person would not pay more for a property than the cost of acquiring an equally satisfactory substitute [3]. The Comparative Transaction Method is generally used for property valuation. This approach to property valuation is based on the comparison of particular and similar properties, which prices were recently realized in the market, which are known. Due to this information, it is possible to individually value the property price. This method is used when at least three realized sales or offers of similar properties are known. The comparative method gives the most accurate picture of realistically viable prices.

- Income approach - The investment method is used to value properties held as investments [3]. During the income approach the valuation is performed based on the capitalization of the potential net income obtained from the rent of the property based on the investment risks relating to the ownership of the property. When this approach is properly applied, it is considered a solid indication of the value of the property for its capacity to produce an income. A valuation approach which involves any valuation method whereby the capital value is found by capitalising or discounting the estimated future income to be derived from the property [4]. One of the most common methods for establishing yield are these: calculation of eternal fixed income (constant yield over a long period of time), yield value established by means of appraisal norm, and calculations for variable yield. [5]

- Cost approach – Valuation model based on costs calculates all current costs which would be needed to re-build the real estate to valuated state, including costs of allotment purchase. [6] The cost approach recognizes that the value of an asset may be represented by the cost to reconstruct or replace it with another of like utility. To the extent that the utility of the asset appraised is less than that of a new asset, the cost new cost be adjusted to reflect appropriate physical depreciation and functional and economic obsolescence. Simply put, the cost approach consists of an estimation of the land value plus the replacement cost of the building in relation to a comparable property [4].

The use of basic valuation approaches is particularly appropriate for objects that are in accordance with their best and highest use, generating adequate returns and are commonly traded on the market. These three basic valuation approaches are supplemented by the additional valuation method defined in IVS 410 Development property [2].

- Residual method - The residual method combines all three basic valuation approaches. The residual method indicates the residual amount after deducting all known or anticipated costs required to complete the development from the anticipated value of the project when completed, after consideration of the risks associated with completion of the project. This is known as the residual value. [3] The residual value, derived from the residual method, may or may not equate to the market value of the development property in its current condition. The residual method is one of the possible methods for the valuation of development projects and is consistent with assumptions reflected in the current market situation.

It is also possible to use Mass Appraisal Models and Automated Valuation Models (AVM) for appraisal of mutually comparable buildings. Several valuation methods have been developed for such purposes, namely direct market models and comparable sales models. [7]

Proper choice of the valuation approach depends on property types, available information and many other assumptions. Market practice will normally indicate the most appropriate valuation method. Based on the experience of the Author all valuation approaches and methods are generally used.

3. Property life cycle

Every real estate asset, regardless of its purpose of use and size, is going thought development over the time. From the initial idea, planning, construction, use, up to disposal. This development is based on the fact that the lifetime of all buildings and constructions is limited. The limited lifespan is a necessity for renewal. This brings us to the gradual obsolescence of the whole process, which we call the "life cycle". British Standards Institution define the life cycle as consecutive and interlinked stages of the object under consideration [8].

The life cycle of real estate can be divided into the basic stages from the point of view of solved problems. Each stage has its own specificities and activities that characterize it for the part of the life cycle. According to the Royal Institution of Certificated Surveyors (RICS), which are world's leading professional body for qualifications and standards in land, property, infrastructure and construction, the main stages of the life cycle are:

- **Land / Greenfield** – Generally is considered as the initial stage of the property life cycle. The land´s possible use is usually defined in the zoning plan / masterplan or other document regulating land use. Investors buy real estate in this stage for further development. Within the RICS property lifecycle this stage recognizes the activities undertaken during acquisition or the management of greenfield areas and estates [9].
- **Investment - Planning** – The subject of this stage is to initiate and define the scope of the future investment intent in one or more variants. As part of the elaborated variant solutions, the feasibility of the project and the financial evaluation of the effectiveness of the individual options are assessed. The main objective of this stage is to evaluate all realization alternatives and to assess the feasibility of the investment project and to provide all background for the investment decision itself. In addition, this planning stage includes the property permitting process. Successful obtainment of zoning and construction permits is an important milestone in the property life cycle. According to RICS it is possible that the design of a building will affect what someone will pay for it and consequently affect its value. This needs to be considered, particularly when making investment decisions [9].
- **Investment - Construction** – It is at this stage that the contractor is appointed, given access to the site and carries out the work until practical completion. The Construction stage of the property usually starts with the obtainment of the construction permit and with an investment decision. The Construction stage is the period when most of the investment funds are spent. The investment stage ends with the completion of the construction work and the occupation of the property.
- **Occupation and Use** – This stage is the longest one in the property life cycle. During this stage the property provides a desired yield. The lifetime of the construction and thus the operational stage of the investment can be prolonged by a possible refurbishment. In the case of a larger investment, intervention that contains elements of the previous stages, it is possible to talk about starting a new investment cycle. An example of such an intervention may be a complete reconstruction requiring a new permitting process.
- **Demolition / Brownfield** – Due to the limited lifetime the property comes into a stage where technical requirements are no longer met or the property´s continued use is not economically viable. The valuation standards do not explicitly hold the appraiser to a value to the level of sustainability addressed in or by the assets being valued. For new property development it is necessary to begin a new investment cycle. The disposal of old buildings and structures is part of the Investment stage of the new investment cycle.

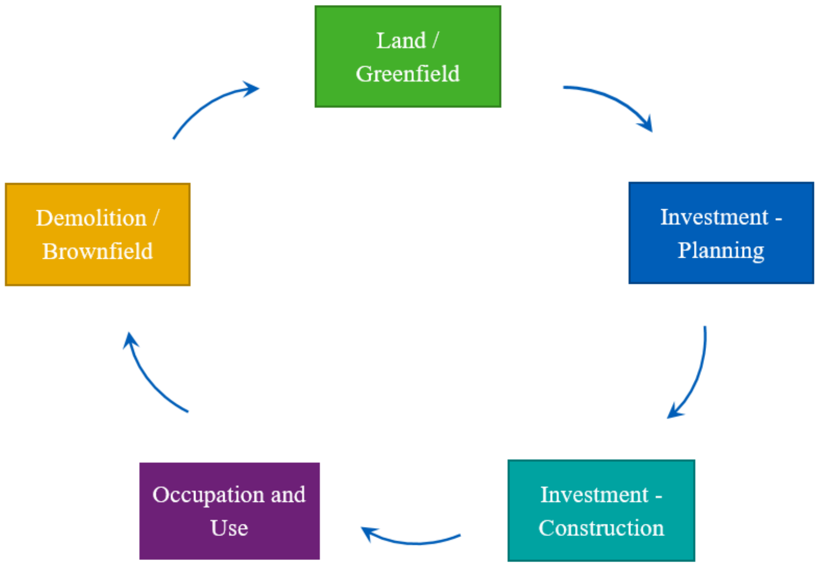

Fig. 1. Property life cycle

4. Valuation methodology in life cycle context

To properly assess the appropriateness of a valuation methodology in its whole life cycle context it is necessary to have a sufficient amount of property valuations and transactions. The internal database of the author is used as a main information source for research.

The internal database includes valuation reports for approx. 300 single properties or property portfolios of different types and locations (mainly Prague and Czech regions but also CEE region). The properties are owned by leading investment groups operating on the Czech market and valued on a regular basis by leading valuation companies in accordance with RICS or IVS valuation standards. The valuation reports are mainly from the years 2015 – 2018. The valuation reports were processed for accounting purposes (fair value) or to support secured lending (market value). The Author´s team is aware of the small differences between Fair value and Market Value of the property however is of the opinion that the impact to valuation methodology is negligible for this research.

Properties with value higher than 1 million € for which the life cycle stage could be clearly identified, and which were valued two years in row (in 2017 and 2018), were selected from the database. In total, 282 individual properties were selected. The selected properties were divided into groups according to their life cycle stage. Subsequently it was investigated which valuation methodology was used for the property valuation. The frequency of valuation methods with respect to life cycle stages is shown in the table below.

Table 1. The frequency of valuation methods with respect to life cycle stages

Stage	Income	Comparable	Residual	Multiple methods
Land/Greenfield	0	14	4	2
Investment - Planning	0	13	13	0
Investment - Construction	0	0	16	0
Occupation and Use	146	26	22	18
Demolition/Brownfield	0	6	2	0

Subsequently it was examined what milestone was considered as a trigger of methodology change. Based on the data obtained the life cycle was divided into phases according to the appropriateness of valuation methodology. A detailed description of each phase is given below.

Phase I starts with the live cycle and ends by obtaining of zoning permit. A typical example of such a property is a land intended for construction or brownfield, which is a land use plan for revitalization. The potential of the property has not already been developed. The property does not generate any or very limited income hence the Income approach for property valuation is not applicable. On the publicly available information sources (land register, real estate advertising, press information, etc.), it is often possible to find sufficient information about comparable transactions. Based on this fact the comparative method is the most appropriate. A Property at this phase may have significant potential for development, so the residual method can be used to support the comparative method. However, at this phase the scope of the future project is not precisely defined and the outcome of the permitting process cannot be determined in advance. Considering the sensitivity of the residual method is not suitable as the main valuation method.

Phase II begins with obtaining the zoning permit and ends with the occupation of the completed property. A typical example of such a property is a development property. This is the period when the investment costs are drawn and the value changes rapidly in a relatively short period. A zoning permit is generally considered to be critical in the realization of a development project and clearly defines the intended scope. On the basis of project documentation for zoning proceedings, it is possible to more accurately determine investment costs. Due to the rapid changes in value during construction the only possible method of property valuation in this phase is the residual method. However, it should be noted that the residual method is really sensitive to key inputs. In order to illustrate this sensitivity a valuation report to office Property valuation was selected from Internal database and a sensitivity analysis of key inputs was performed.

Table 2. Sensitivity analysis of residual method

Key input	Difference in key input	Difference in Residual Value
Estimated rent	-10%	-24,4%
Lettable area	-10%	-10,0%
Capitalisation rate	-10%	-25,4%
Construction costs	+10%	-15,4%
Soft Costs	+10%	-2,0%
Financial costs	+1% p.a.	-4,5%
Construction time	+1 Year	-8,9%
Development profit	20%	-5,9%

As Table 2 indicates only small changes in variables such as Estimated rent, Capitalization rate or Construction costs will have a disproportionate effect on the Residual value. The use of a comparative method is also possible until a building permit is obtained and the actual implementation commences. From this milestone the use of a comparison method is already problematic.

Phase III is the longest throughout the life cycle and corresponds to the Occupation and Use stage defined by RICS. Around 75% of the properties in the Internal database are in this phase. The phase begins with the occupation of the completed property and ends with the termination of its use. At this phase, the Property is usually consistent with its best and highest use and generates appropriate income. Valuation methods based on available information about comparable transactions or modeling future income are most commonly used at this Phase. In general, a comparative approach is more appropriate for the valuation of residential properties and an income approach is more appropriate for the valuation of commercial properties such as offices, retail, warehouses, etc. However, in case of sufficient information both valuation approaches can be taken into account.

Phase VI starts after the end of property use period. In this phase, properties are usually in poor technical condition which do not allow other economically interesting uses. If there is a new and better possible use, there is usually a smooth transition between Phase VI and Phase I and the Property begins a new life cycle. The cost of ecological disposal is then part of Phase 1 of the new life cycle. The property in this phase no longer generates sufficient revenue. The valuation approach used for the Property valuation at this phase is practically the identical as in Phase I.

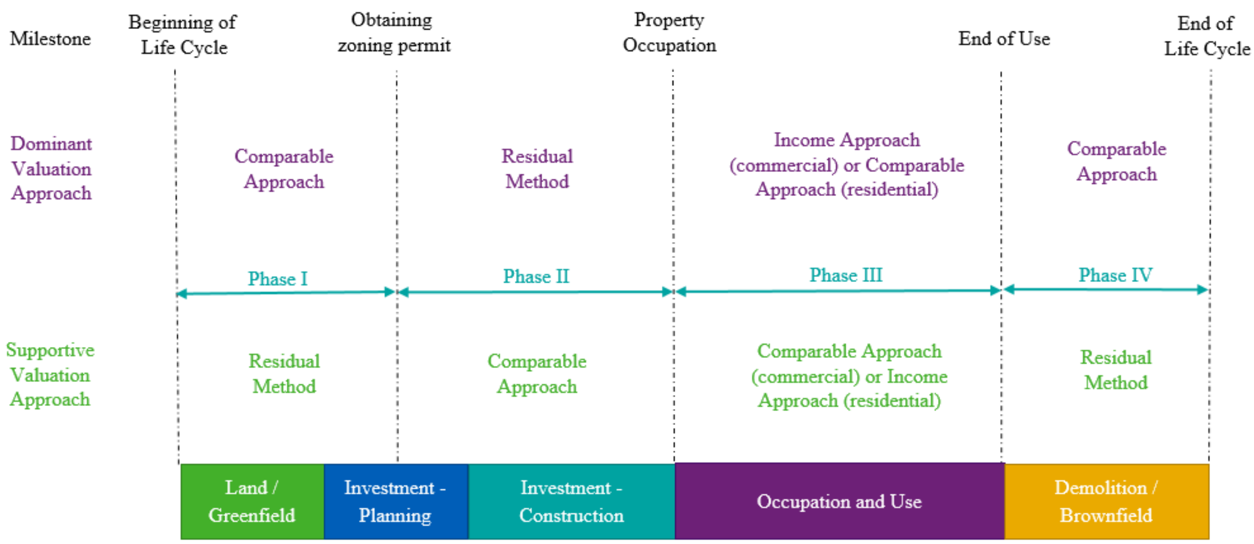

Fig. 2. Appropriateness of valuation methodology in a life cycle context

In addition to the valuation reports, the Author´s team collected reports of market research prepared and published by different real estate agents for the Czech Republic. This information mainly relates to the prime yields, prime rents, occupancy level, occupancy level or residential prices. Further, this market research is used as a source for market trends and information of the details of actual transactions on the market. According to the publicly available benchmarks the general year-to-year increase in values on Czech real estate market was 5% -10% [12,13].

Properties with a significant annual difference in value were selected from the surveyed sample. Year-to-year changes (increase or decrease) in value higher than 25% is considered as the significant annual difference. In total 51 properties were identified. The research was focused mainly on properties where the valuation methodology comparing to the prior year was changed due to the progress in the property life cycle. These groups are highlighted in grey.

Table 3. Triggers of significant annual difference in value

Number of properties	Valuation approach used 2017	Phase 2017	Valuation approach used 2018	Phase 2018	Key trigger of change
13	Residual	Phase II	Income	Phase III	Progress in development/Occupation and use
7	Residual	Phase II	Residual	Phase II	Progress in development
6	Comparable	Phase I	Residual	Phase II	Zoning/construction permit obtainment
6	Income	Phase III	Income	Phase III	Property refurbishment
4	Residual	Phase I	Residual	Phase II	Zoning/construction permit obtainment
4	Income	Phase III	Income	Phase III	New rental contract/significant change in occupation
3	Comparable	Phase I	Residual	Phase I	Change of valuation methodology
2	Income	Phase III	Residual	Phase VII	Abandonment /planning of new development
1	Income	Phase III	Income	Phase III	Change of Appraiser
5	Diversified				Multiple reasons

The survey shows that approximately 50% of the significant annual changes in value are caused by the progress in the life cycle of the property. Key triggers of the significant change in value in life cycle context are: progress in development, property occupation, zoning/construction permit obtainment and abandonment of the property. Based on this fact, the Author´s team notes that the suitability of valuation methodology regarding the life context has a significant impact on the property valuation.

5. Conclusion

Real estate valuation is indispensable for investors, banks, auditors and other institutions. Valuation methodology is based on the workings of a free market economy. Proper choice of which valuation approach depends on property types, available information and many other assumptions. Market practice will normally indicate the most appropriate valuation method.

During the property life cycle there are several milestones that can be seen as breaking points which determine appropriate valuation methodology. Achieving these milestones in valuation practice results in a change in valuation methodology. A change in valuation methodology implies a number of new assumptions or key inputs and often leads to a significant change in value. The Author´s team examined the valuation methodology during property life cycles and focused mainly on significant year-to-year changes in value. An internal author´s team database was used as a source of information. The database contains a sufficient number of properties valued on a regular basis. The valuation reports were processed by leading valuation companies in the Czech Republic.

The most significant year-to-year changes in value were caused by the change in valuation methodology due to the progress of real estate to the next phase in the life cycle. For these changes a trigger for a shift in methodology was investigated. The most significant milestones in real estate valuation context are considered progress in development, property occupation, zoning/construction permit obtainment and abandonment of the property. These milestones can be seen as the boundaries that separate the suitability of using valuation methodology over the life cycle.

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Monitoring Distraction of Construction Workers Using a Wearable Electroencephalography (EEG) Device

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Abstract

Distraction is a major cause of unsafe behaviors and decreased safety performance in a high-attention demanding construction environment. However, few studies have drawn attention on cognitive characteristics of distraction and the method to detect it quantitatively. To fill the gap, this study investigates the correlation between distraction and mental activity using EEG device, aiming to provide a real-time approach to monitor the worker's distraction objectively. In this study, sustained attention to response task (SART) has been employed to induce the occurrences of distraction in the simulated construction safety inspection tasks. The recorded EEG data was divided into two groups corresponding with task performance: focused and distracted. By analyzing the data through pre-processing and feature extraction methods, the objective is to examine indices that enable to distinguish these two statuses based on time and frequency domain. The metrics proposed are estimated to be associated with cognitive functions like attention deficit and attention allocation, herein serve as an objective assessment of an individual's sustained attention degrees and cognitive failures. Accordingly, this study facilitated the development of cognitive features of distraction theoretically and made it possible to detect and control the inner distraction leading to unsafe behavior or decreased task performance in practice.

Keywords: distraction; EEG; sustained attention; unsafe behavior; job site safety

1. Introduction

Although construction safety management has been largely enhanced over recent years, the high incidence of accidents and huge financial cost recorded at construction projects among all industry sectors still highlight safety management to deserve discussed. In the United States, fatal occupational injuries in the construction industry have the largest proportion from 2003 to 2016, more than transportation and over twice than manufacturing [1]. Across the European Union, the construction sector accounts for 21% of fatal accidents in 2015 [2]. Catastrophic accidents undoubtedly mean tragedies to both families and construction program, causing irreversible damage to the health of suffers, and impeding smooth project running. A large body of research pays attention to investigate common and fundamental contributors to injury and fatality rates[3,4]. Evidence suggests that 88% of the accidents of construction programs among proximal factors were caused by inappropriate safe behavior [5]. Workers' unsafe behavior depends on a variety of factors, among which external factors include site conditions, safety culture, and climate, training and education,

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supervision and management, internal factors related to individual conditions such as safety incentives, attitudes working experience, social relations, attention allocation, alertness, emotion, fatigue and stress [6] .

Individual internal factors such as stress, fatigue, alertness that play a significant role in shaping the safety behavior of workers have been studied [7,8]. However, research addressing the link between mind-wandering and safety behavior remain inadequate in spite of ubiquitous distraction sources at the site. Not only the work quality decrease with distraction but also the likelihood of improper operation, careless accidents, and fall accidents increases, even impact on project cost and schedule [9]. Dynamic environments and potential safety hazards everywhere require construction workers to keep vigilant. Thirty-four workers were interviewed at the site about the causes of high-altitude falls and found that 33 workers agreed that negligence and distraction were one of the major causes of the fall [10]. Employees with repetitive and monotonous tasks like heavy machinery operators, signalmen, rebar tying workers are more prone to make poor safety judgment because of stuck in distraction. Distraction potentially derives from environmental or personal-related factors, like noise, moving vehicles, conversation with colleagues and safety incentives, body discomfort, fatigue, depressed mood or family bothering.

As various sources of distraction cannot be identified and eliminated completely within complex construction context, especially personal-inner interference, more important is to capture distraction state and manage properly than recognize each potential source. Although brain waves of distraction have been studied within medical and cognitive science domains, such findings cannot fit well in the construction industry practically for the nature of task and context. Therefore, it is yet not clear how to monitor the mind-wandering of workers real-time to avoid unsafe outcomes caused by distraction. To fulfill the research gap, an objective measurement approach with wearable EEG device is proposed to detect workers' distraction, aiming to inhibit frequency and address the occurrence of mind-wandering at actual sites. The paper provides insight into quantitation of distraction utilizing sustained attention to response task (SART). More specifically, the authors attempt to build correlates between brain state and behavior performance and discover indices regarding distraction after analyzing EEG data. In addition to enrich knowledge body, understanding of detecting distraction can help minimize adverse effect on work quality and avoid unexpected safety outcomes.

2. Literature Review

2.1. Distraction

In fact, many versions of distraction definition can be found in the literature, and what they have in common is divert the attention of primary task to something else and cannot pay full attention to perform the task at hand safely and efficiently [11,12]. Distraction usually displays in forms of yawn, drowsiness, eyes wandering, talking with colleagues, playing mobile phones, texting message, eating or drinking, looking around, or mind-wandering despite look like focused. Distraction can be into two types: mental and physical, also known as internal and external distracted, the main difference of which lies in the existence of physical changes and external events [13]. At present, there has been an enormous increase in the number of studies examining distraction in the area of education, transportation, medicine, cognition, and neuroscience by emerging physiological technologies but lack research in the area of construction safety. Combined with physiological measurement, students' neurofeedback to distinct learning content and media is useful to facilitate improving the quality of learning and teaching [14]. Likewise, drivers urgently need sustained attention than students due to distraction is confirmed that account for substantial crashes and traffic accidents [15]. The construction safety department gradually recognized the adverse effect of distraction and Occupational Safety and Health Administration (OSHA) set up special regulations to restrict the distraction of mobile phones aiming at crane operators. A recent study of workers has unveiled that distraction indeed impede hazards recognition levels and the rationality while perceiving safety risk through an experimental attempt [16]. Chukwuma Nnaji conducted extensive literature and a survey to summary distraction sources and ranked the impact of each distraction factor, which construction personnel agreed that poor attitudes, lack of safety resources, lack of familiarity with equipment, site crowding play a vital role in work safety and quality [9]. However, the issue of distraction and its impact on safety performance, and its sources and countermeasures have been under-researched from a scientific and systematic perspective in the field of construction. With respect to solutions, Seli claimed that different countermeasures should respond to different types of mind-wandering [17]. Except for eliminating sources of distraction, capturing distraction state is crucial to control the phenomenon and subsequent results.

The tools to assess cognitive state in the current study (alertness, tension, distraction, anxiety, cognitive overload) are divided into two categories: traditional subjective ratings and objective measures. Subjective response primarily consists of self-reports, and objective measures mainly contain performance measures (reaction time, error rate, task accuracy) as well as psychophysical methods. Mindful Attention Awareness Scale, Cognitive Failures Questionnaire (CFQ), Mind Wandering Scale (MWS), Attention-Related Cognitive Errors Scale (ARCES) and Karolinska Sleepiness Scale (KSS) were put forward to estimate the level of attention and mind-wandering. However, the retrospective method belongs to post-evaluation, which lost timeliness and affected by individuals' understanding deviation of questions to a large extent. Behavioral metrics in driving contain speed variability, lane deviation, the standard deviation of lateral position (SDLP) and steering reversal rate (SRR), to serve as a performance method to seize distraction. Nevertheless, these metrics cannot be applied to construction personnel for the nature of task and scenarios at the workplace. Emerging psychophysical technologies has been adopted in recent years, namely, endogenous eye blinks (EOG), heart rate activity (HRV), Electromyogram (EMG), wearable electroencephalography (EEG) devices, functional near-infrared spectroscopy (fNIRs) and functional magnetic resonance imaging (fMRI). EEG outperforms other wearable devices to record brain activity on account of its non-invasive, high time resolution and portable characteristics.

2.2 EEG Application

The reliability of wearable EEG devices to assess mental state has been validated by considerable research. Results of a breath counting task suggested a significant reduction of alpha-band activity combined with a diffuse increase in theta band activity, and the researcher found there was a similar increase in theta band as that reported by a study measuring frontal sites during mind wandering [18]. Conversely, the research conducted by Carryl L. Baldwin et al., combined driving task performance with EEG detection and the findings suggest periods of mind wandering were associated with increased power in the alpha band of the electroencephalogram (EEG), as well as a reduction in the magnitude of the P3a component of the event-related potential (ERP) in response to the auditory probe [19]. However, many articles reach a consensus that oscillatory activity in the alpha band of the EEG is suggested to be related to attention processes specifically the degree to which attention is allocated internally vs. externally [20]. In addition, research suggested alpha power is associated with lapses of attention to external stimuli [21]. A recent study also proposed EEG to detect mind-wandering and aimed to predict the mind-wandering state of a person, the results of which revealed reduced electrodes can also achieve prediction effect and the non-linear Support Vector Regression (SVR) model showed significantly better precision than linear SVR model [22]. However, specific metrics to recognize if a worker is distracted has not been built, and whether it can apply in the area of construction remain unclear. Up to now, EEG has been proposed to be utilized at construction sites to assess mental workload, stress and vigilance levels [23,24]. The construction workers' perceived risk level can be effectively reflected and quantified by EEG signals such as frequency, power spectrum density, and the relationship between vigilant attention and forehead EEG was identified most close [25]. In a word, EEG is plausible enough as an estimator of construction workers' cognitive state through extracting and processing features of different brain states.

3. Methodology

3.1 Experiment

Ten healthy postgraduate students completed the SART experiment, of which half is male, and the other half is female. The age range from 20-30 years old and all participants have normal or corrected-to-normal vision. The stimuli were presented in the form of pictures against a grey background on a computer screen, which includes two types of pictures appearing on the screen randomly. They are pictures workers wearing with and without hardhat. Those pictures are collected from Google search engine, namely, non-target and target stimuli, of which the proportion of non-target and target trials is 11:1. To detect internal and external distraction, two groups of experiments were designed. Each trial in the first experiment is only a picture associated with the construction site, but in the second set of experiment, two pictures are presented including a picture related to hardhat judgment and the other is interference irrelevant with construction. The EEG device used in this research is Emotiv-EPOC with 14 electrodes as shown in Figure 1. The experiment is supported by Paradigm, one of psychology software and the version is free trial version: v2.5 for Windows.

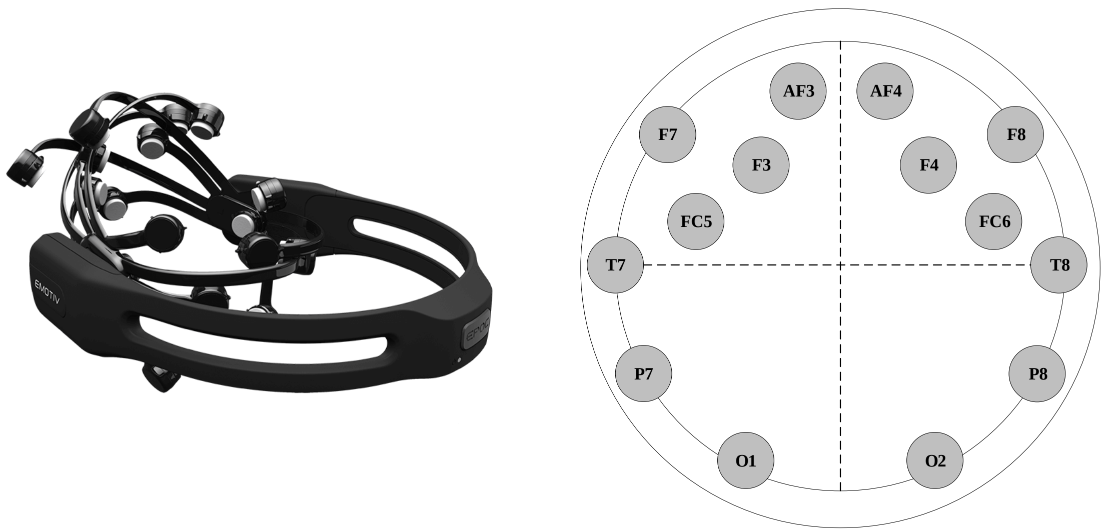

Fig. 1. EEG Headset/Sensors Location

Initially, participants were informed of the experimental procedure and were required to rest for 5 minutes. Then participants were instructed to respond to pictures including hardhat as quickly and focused as possible when the stimuli appear on the screen. If the worker wears a hardhat, called non-target stimuli, participants need to press the left arrow button on the keyboard; otherwise the right arrow button when the target appears. Meanwhile, the participant's behavior response and EEG brain activity were registered synchronously. Each trail just last 1000 milliseconds on the screen until a timeout occurred. A block consisted of 60 trials, so each participant is required to complete 4 blocks during each group, that is 480 trials totally. After they complete each block, participants will be asked: "Are you distracted just now?" The participants need to answer from 1 (very focused) to 5 (always distracted). "Are you aware that you are distracted?" The participants need to select from 3 options: very focused, intentionally distracted and unintentionally distracted. The duration of each question is about 5 seconds. The whole experiment procedure is demonstrated as Figure 2. Given that sufficient time is provided to perform each trail in 1000 ms, so participants are required to keep sustained attention to react in the limited duration, or they were identified distracted at the moment when giving an error response.

3.2 Data Processing

Data collected during the experiment include self-ratings, behavior performance and brain waves. Self-ratings serve as a subjective response of distraction degrees, and the role of behavior data is to provide an objective benchmark and label synchronous brain data. The purpose of analysing data is to find credible indices associated with a state of distraction. Behavior data recorded by Paradigm automatically contains reaction time (millisecond) and error labels (binary number) of each trial, as well as a self-rating of each block. Recorded data are analyzed by the statistical approach utilizing SPSS software, and the Spearman coefficient is selected to calculate the correlation between self-assessment and actual error rate.

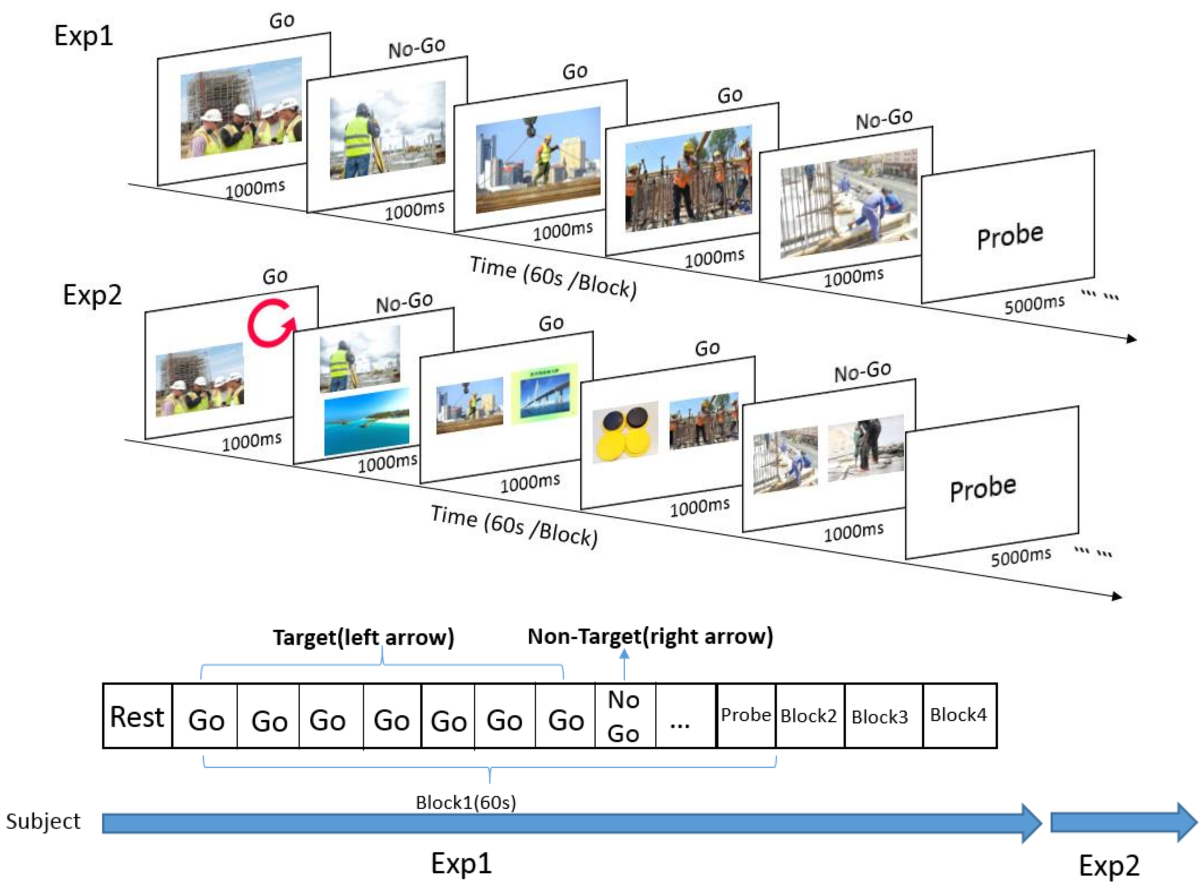

Fig. 2. Experiment Stimuli/Procedure

The most important stage is how to extract the features of EEG signals and validate the reliability of indices. The proposed EEG signal processing method consists of three phases: pre-processing, feature extraction, classification, as illustrated in Figure 3. EEG pre-processing is vital because EEG raw data is susceptible by various artifacts such as white noise, line noise, eye blink, eye movement, muscle artifacts, sweat pollution, motion interference and electrocardiogram (ECG). The main methods are Finite Impulse Response (FIR) band-pass filter from 1-60Hz to filter noise, and a notch filter at 50Hz was applied to eliminate power line interference. Independent component analysis(ICA) method supported by EEGLAB was used to reject eye movement and muscle artifacts. In the actual preprocessing, several subjects showed ECG artifacts, which were also removed by ICA. Then data were segmented into epochs as trail duration and regrouped into 'distracted' and 'focused' according to error labels. After pre-processing, signals can be analyzed in time, frequency or time-frequency domains to extract significant metrics. Feature extraction methods include Fast Fourier transform (FFT) to do frequency analysis, short-time Fourier transform (STFT) to extract time-frequency information, and wavelet decomposition to focus on frequency bands of interest. To validate the reliability of indices, support vector machine (SVM) is suitable for the binary classification problem in this experiment.

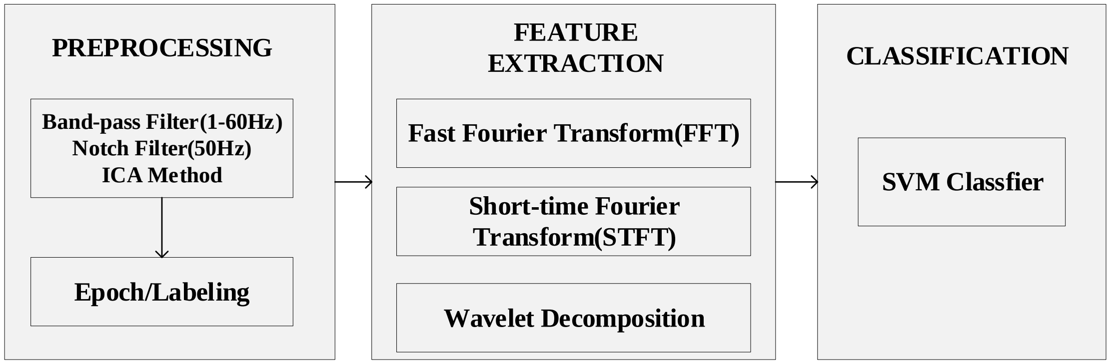

Fig. 3. EEG Data Processing Framework

4. Preliminary Results

In both sets of experiments, response time in Table1 when making mistakes (735.54 ms vs. 740.15 ms) was markedly longer than that of correct judgment (553.67ms vs. 588.98 ms). Participants cannot perform the task effectively as usual when distracted despite enough time. Comparing two groups, the correct response time in the second group with unrelated interference (588.98ms) is longer than that in the first group (553.67 ms), but the incorrect response time in two groups make no difference (735.54 ms vs. 740.15 ms). When the workers are disturbed by visual images unrelated to the primary task, it will take longer to process the task. Likewise, the proportion of error rate in the second group was significantly higher than the first group, 11.08% and 7.08% in Table 2 accordingly. Surprisingly, the correlation between subjective judgment and accuracy rate is lower than 0.6 excluding subject 6, so subjective judgment of distraction degrees has great deviation in the evaluation of the actual error rate.

Table 1. Mean response time of each block in two experiments.

Response time (ms)	Exp1		Exp2	
	Correct	Incorrect	Correct	Incorrect
Block1	560.76	763.68	607.94	784.19
	(150.04)	(301.12)	(159.60)	(316.97)
	563*	37*	555*	45*
Block2	561.09	658.23	602.42	790.80
	(139.35)	(336.67)	(153.38)	(334.38)
	572*	28*	540*	60*
Block3	560.15	763.71	580.54	725.83
	(154.17)	(288.54)	(161.78)	(318.15)
	543*	57*	518*	82*
Block4	532.31	726.28	563.25	691.45
	(158.23)	(291.23)	(164.68)	(296.10)
	551*	49*	521*	79*
Total	553.67	735.54	588.98	740.15
	(150.88)	(300.03)	(160.63)	(316.23)
	2230	170	2134	266

Note: Standard deviation is in brackets. * is the total number of correct and incorrect trials in each block.

Table 2. The error rate of two experiments and correlation with self-reports.

Subjects	Exp1	Exp2	Spearman coefficient
1	1.25%	6.67%	NaN
2	7.5%	11.67%	0.279
3	7.5%	10%	0.323
4	9.58%	15.83%	0.201
5	10%	18.75%	0.567
6	5.83%	7.5%	0.689
7	5.83%	12.5%	0.446
8	7.08%	5%	-0.394
9	7.92%	8.75%	0.399
10	8.33%	14.17%	0.028
Average	7.08%	11.08%	0. 047

5. Conclusions

It can be concluded that monitoring sustained attention subjectively exist assessment bias and cannot be implemented continuously in construction activities. Under the premise without hindering work, real-time detection by wearable EEG is able to response personal attention-related changes immediately than preventive measures like safety training and job hazards analysis. Compared with the causation analysis of distraction, detection is a straightforward intervention. In addition, the application range of findings are not limited in construction but drivers, surgeons, pilots and other jobs demanding sustained alertness. The main drawback of the experiment is that it is performed in a contained environment instead of a real construction job site. However, it was confirmed that wearing an EEG device at a construction workplace is completely practicable [26]. Moreover, the task in the experiment merely simulates one of the construction activities, sorts of safety activities are supposed to be considered in future works. Excluding visual interference, the distraction of workers is caused by various factors like fatigue, bad mood or noise around in daily work, yet it remains unclear whether the extracted features can be applied to all scenarios. Moreover, subjects participating in the experiment are not real workers, so it is still needed to examine that the difference between postgraduates and workers. Beyond this, it is necessary to explore the effect of demographic features like gender, age, and working experience on workers' sustained attention.

With regard to research about cognitive behavior by EEG, improving the accuracy of filtering is essential due to vulnerability during EEG signal acquisition. In addition, further research is needed to improve the accuracy of feature extraction because brain waves exist strong latent ability, and cannot be purely interpreted into corresponding cognitive behavior from a few features. In other words, forward reasoning from behavior to features does not promise the reliability of backward chaining from features to represent behavior.

Acknowledgments

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Probabilistic risk appraisal and mitigation of critical infrastructures for seismic extreme events

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Abstract

The importance and the interdependencies of critical infrastructures such as power and water supply, communications, and healthcare is increasing continuously and constantly. Most of the vital services for the private and the public sectors depend on the continuous performance of critical infrastructures. However, the last decades' extreme events reveal a significant gap between the preparedness of critical infrastructures and the actual risk that those infrastructures are exposed to in case of seismic event. In this research a methodology is developed to appraise and mitigate the risk that critical infrastructures are exposed to in case of seismic events. The proposed method is designated also to act as decision support tool for the selection of the most advantageous strategy to reduce the risk expectancy for extreme seismic events. A Probabilistic Seismic Hazard Analysis (PSHA) approach is used in order to reflect a variety of possible seismic scenarios and overcome the uncertainties regarding to the timing, the location, and the magnitude of an earthquake. The seismic vulnerability of different components is evaluated by adjusted fragility curves and Fault-Tree-Analysis. The seismic risk function, that expresses the expected risk of the system for a given ground motion intensity, is derived according to the occurrence probabilities of the earthquake, the seismic vulnerability of different components, and the expected consequences. This paper introduces the developed methodology and demonstrates the key steps through two case studies of oil pumping plant and oil tank farm. The pumping plant case study demonstrates the development of the risk function and examines the contribution of a possible mitigation strategy on the overall risk expectancy. The oil tank farm case demonstrates a derivation of an exclusive fragility function for critical infrastructures facility. This methodology provides a novel analytical and decision-support tool that integrates between the components adjusted fragility curves in the risk assessment and the consequent mitigation step; the optimal mitigation strategy is derived from the fragility parameters reflection on the total risk function.

Peer-review under responsibility of the scientific committee of the Creative Construction Conference 2019.

Keywords: Critical infrastructure; Risk appraisal; Risk Mitigation; Fragility curves; Earthquakes;

1. Introduction

Critical Infrastructures (CI) play a crucial role in the normal performance of the economy and society. Over the last decades the amount and the variety of critical infrastructures grew rapidly, and the interdependency between them increased constantly; consequently, more and more essential services depend on the continuous performance of one, two or even more critical infrastructures such as power, water supply, communications, etc.

As was observed in previous studies, there is a significant gap between the stability and the preparedness level of CIs for seismic events and the actual damage that those facilities are exposed to in a case of a seismic event [1-2]. The consequences of the latest seismic events emphasize the importance to mitigate the seismic risk by increasing the

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preparedness of CIs and ensuring reliable and robust performance on a continuous basis, particularly during and after the occurrence of extreme events. Implemented mitigation strategy is derived according to the financial constraints and depends on decision makers' policy. Therefore, at first, in order to clarify the actual risk that CIs are exposed to in case of seismic event the risk should be quantified. Subsequently, in case the risk is not acceptable, different mitigation strategies must be examined in order to select the most optimal strategy, in accordance with the economic feasibility.

The major objective of this research is to develop a probabilistic methodology that examines the preparedness of critical infrastructures through an appraisal of the risk that CIs are exposed in case of seismic events and provide a decision support tool for risk mitigation. Prior methodologies for risk appraisal [3-6] presented procedures that offer tools such as fragility curves, fault-tree-analysis (FTA), and logic tree in order to appraise the risk of different components. Those methodologies presented tools to appraise the risk for existing generic infrastructures based on empiric data. However, those studies didn't examine different mitigation strategies and their effectiveness on the risk reduction and didn't derive the optimal strategy. Moreover, those methodologies are mainly used in order to appraise the risk as a result of a particular earthquake event.

The present methodology is intended to expand prior risk appraisal tools such as fragility curves and fault-tree-analysis and implement them as a decision support tool for policy making. This methodology intends to quantify the seismic risk by a probabilistic seismic analysis of a variety of possible seismic scenarios and examine different mitigation strategies in order to obtain the optimal mitigation strategy under the given financial constraints.

2. Methodology

2.1. Seismic Hazards Identification

The seismic risk for each CI's component is identified according to the location of the facility according probabilistic seismic hazard analysis (PSHA) as presented by [7]. The PSHA approach is intended to consider all possible scenarios according to geological data about the possible earthquake sources, and the probability of magnitude and intensity occurrence that is associated with those events. The PSHA approach requires ground-motion attenuation models that estimate the expected ground-motions at a given site as a result of different intensity and location earthquakes, several studies offer attenuation models for different location and regions [8, 9]. This step yields an Annual Rate of Exceedance curve (PE_A) as a function of a given ground motion intensity measure (IM); when in most cases, for above-ground structures the IM is expressed in terms of peak ground acceleration (PGA) [10-12].

2.2. System's Seismic Vulnerability

In this step, the expected damage state as a result of a seismic event is formulated in terms of fragility curve. The fragility curve expresses the probability of reaching or exceeding certain damage states for a given level of IM [13-16]. This function is fully defined by determination of two parameters: median capacity of the component to resist the damage state (θ) and standard deviation of the capacity (β).

$$P[DS \geq ds|IM = x] = \Phi\left(\frac{ln(x/\theta_{ds})}{\beta_{ds}}\right) ; ds \in \{1,2, \dots N_D\} \quad (1)$$

Eq. 1 expresses a formulation of a fragility function. P stands for a conditional probability of being at or exceeding a particular Damage State (DS) for a given seismic intensity, and x is defined by the earthquake Intensity Measure (IM).

Where,

- DS Uncertain damage state of a particular component. {0,1,... Nn}
- ds A particular value of DS

N_D Number of possible damage states

IM Uncertain excitation, the ground motion intensity measure (i.e. PGA, PGD, or PGV)

x A particular value of IM

Φ Standard cumulative normal distribution function.

θ_{ds} The median capacity of the component to resist damage state ds measured in terms of IM

β_{ds} Logarithmic standard deviation of the uncertain capacity of the component to resist damage state ds

In this step, the fragility parameters can be yield on the existing values that are available for generic components based on prior studies [4, 6, 12, 17]. However, in the case of a unique system or component, it is preferable to develop exclusive values for the system in accordance with the fragility of the sub-component.

2.3. Damage Assessment due to seismic Extreme Events for different components

This step associates a damage ratio (DR_i) with each damage state; DR_i expresses the percentage of the total replacement value of a component corresponding to damage state i. Subsequently, since the damage ratio is associated directly with the damage state, the expectant damage ratio of a component (DR_c) can be calculated as follows:

$$DR_c = \sum_{ds} DR_i \cdot P(ds_i|IM) \tag{2}$$

Where

DR_i Damage rate of the damage state i

$P(ds_i|IM)$ Conditional probability of being in a certain damage state i for a given IM

Furthermore, the expected repair cost (RC_c) of the component for a given IM can be calculated regarding to the replacement value (RV_c); when the RV_c expresses the total replacement cost of the component. Thus, one can calculate the expected direct damage of the component for any given IM as follows:

$$RC_c(IM) = RV_c \cdot \sum_{ds} DR_i \cdot P(ds_i|IM) = DR_c \cdot RV_c \tag{3}$$

2.4. Risk Appraisal according to expected damage

The product of this step is a seismic risk curve that presents the expected annual risk for any given value of IM. Since risk represents the potential impact and loss and it is defined as the product of the occurrence probability and the expected consequences, this curve is developed by multiplying the annual rate of exceedance curve with the direct damage curve by matching between the PGA values in both curves and links the expected consequence and its probability to occur. This matching produces a curve that correlated between the expected damage in terms of annual expectancy of risk and the PGA.

$$R_A(IM) = RC_c(IM) \cdot PE_A(IM) \tag{4}$$

Where

$R_A(IM)$ Annual risk for a given IM

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$RC_c(IM)$	Replacement cost of the component for a given IM
$PE_A(IM)$	Annual rate of exceedance of a given IM

2.5. Risk Mitigation

In this step, different mitigation strategies are examined in order to predict the effectiveness of each mitigation strategy on the preparedness of the CIs by quantifying the reduction of risk followed by implementation of each strategy. Each examined mitigation strategy has different effects on the robustness and the resilience of the system which is reflected in different parameters of the fragility curve; those changes will affect the risk level. Subsequently, the optimal strategy is selected according to the level of risk reduction given the economic constraints.

3. methodology implemention: Case study 1

This chapter demonstrates a conceptual implementation of the methodology through a case study of an oil pumping plant (PP). Pumping plants serve to maintain the flow of oil across pipeline systems. They are located at certain intervals along the pipeline network to ensure the transport over long distances and around the storage facilities when the pressure must be increased due to friction losses. In addition, Pumping is also required to transport oil uphill wherever this is required due to topographic conditions.

The annual rate of exceedance curve depends on the specific location of the facility. Therefore, in this case, the pumping plant is assumed to be located in Beer-Sheva, Israel. A simplified annual rate of exceedance curve (Figure 1) was derived based on the values that were published by the Geophysical Institute of Israel report [18]. In this report, the attenuation is based on the model of [19] which has a good correlation to the Middle-East seismic patterns. This attenuation model considers a sufficient range of magnitudes (4-8.5g.) and allows considering the effects of weak seismic areas. Moreover, this attenuation considers the main parameters of site effect such as: Magnitude (M), distance from rupture (R), fault mechanism, and soil stiffness.

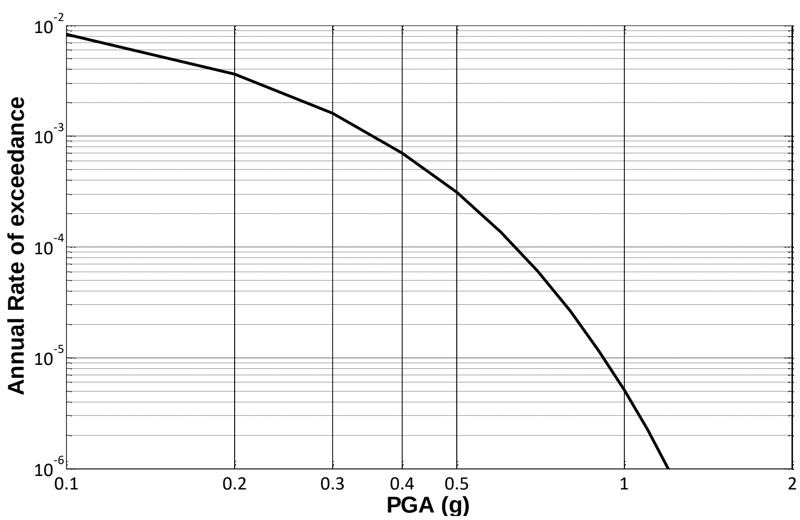

Figure 1 - Annual rate of exceedance curve for west Beer-Sheva region

According to [6] the failure of a pumping plant is most likely to occur as a result of damage to one of its main sub-components: the building, one or more pumps, electrical equipment, and electric power and backup systems.

In this case, the fragility parameters are based on the values proposed by [4] for unanchored pumping plant (Figure 2), the damage ratio of the tank is based on the estimate damage ratio that proposed by [4], and the replacement cost for a pumping plant is estimated at 1M US$.

Table 1.Damage states definitions and parameters of an oil pumping plant and the damage ratio values as proposed by [4]

Damage state (Ds_i)		**Damage Definition**	θ	β	DR_i
Ds_1	Slight/minor	Light damage to building	0.12	0.60	0.08
Ds_2	Moderate	Considerable damage to mechanical and electrical equipment, or considerable damage to building	0.24	0.60	0.40
Ds_3	Extensive	Building being extensively damaged, or pumps badly damaged.	0.77	0.65	0.80
Ds_4	Complete	Building being in complete damage state	1.50	0.80	1.00

Following the above parameters (Table 1), the risk function is derived by an integration of the annual rate of exceedance curve with the fragility curve, the damage ratio (DR_c), and the replacement value (RV_c). The risk curve analysis shows that low-moderate ground accelerations, where the exceeded PGA is less than 0.8g, have a major contribution to the total annual risk of the pumping station (Figure 3).

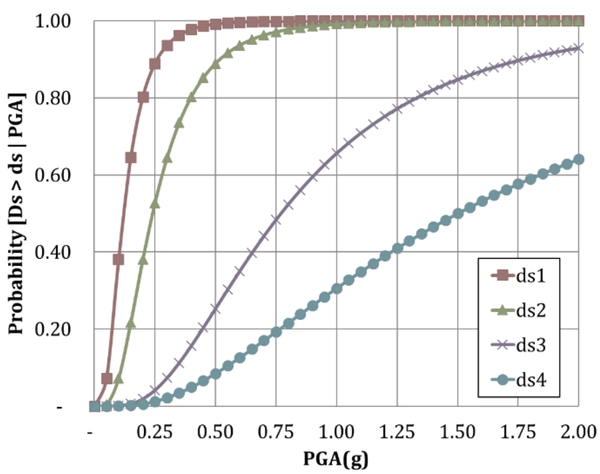

Figure 2 - Fragility curve for pumping plant

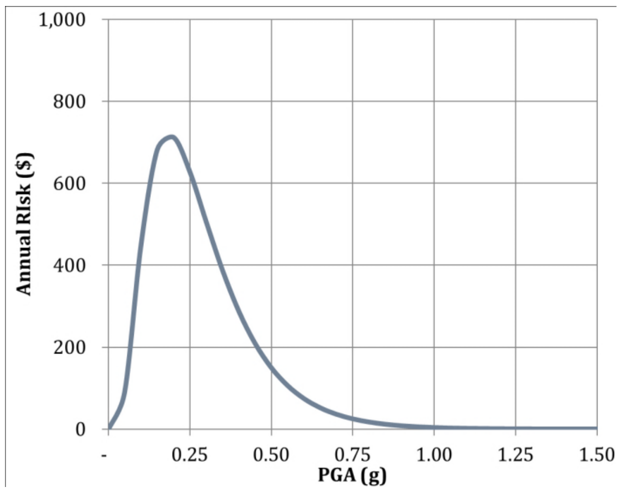

Figure 3 - Risk curve for pumping plant

One of the possible methods to reduce the potential damage of the PP in case of seismic event is anchoring the subcomponents of the station. This strategy is increasing the resistance of the subcomponents to overcome moderate level ground accelerations and subsequently increases the robustness of the pumping plant for seismic events. Implementation of this strategy modifies the fragility curve parameters for ds_1 and ds_2, which gives a relatively high probability to exceed this damage states in case of moderate ground accelerations for the unanchored plant while anchoring the subcomponents reduces the probabilities to exceed ds_1, ds_2 in case of moderate ground alccelerations (Figure 4). This mitigation strategy reduces the total risk of the pumping plant. The reduction profoundly affects the damage that expected as a result of moderate ground motion. An analysis of the derived risk curves for unanchored and anchored plants shows that anchoring the components can reduce the risk by about 27% (Figure 5).

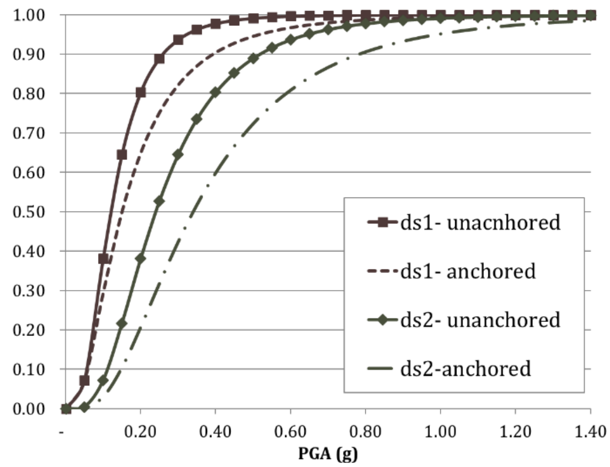

Figure 4 - Comparison of ds_1 and ds_2 for anchored and unanchored pumping plant

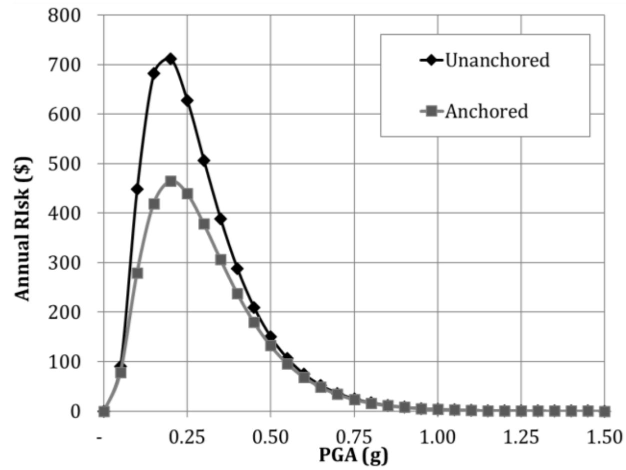

Figure 5 - Comparison of the risk curve for anchored and unanchored pumping plant

4. Seismic vulnerabilty function: Case study 2

This chapter demonstrates the derivation of a fragility function for exclusive critical infrastructures facility through a case study of an oil tank farm. In case of an exclusive facility or component of a system, it is desired to derive and use the best fit fragility curve. The main purpose of this step is to produce a unique fragility based on an aggregation of the fragilities of the sub-components (Figure 6). In this example, it is considered that the oil tank farm is composed of five main sub-components: building, storage tanks, power grid, backup generator, and mechanical equipment.

4.1. Building

The control center of the farm is in a low-rise building. The building serves for the control and the supervision of the ongoing operation of the farm. In this case, the building is a one-story RC structurer. The fragility parameters are based on [6].

4.2. Tanks

Oil storage tanks are used for storage of different petroleum products for a long or a short-term time; the oil farm consists of several storage tanks. The modern oil storage tanks are varying from 12-76m in diameter with heights to diameter ratio (H/D) less than one. The most common design type of tanks is cylindrical ground-supported tank due to their efficient resistance to hydrostatic pressure and can be easily constructed. In addition, most of the oil storage facilities are composed of welded steel with floating roof. Several fragility parameter sets are offered by the literature based on empirical data. The HAZUS procedure provides data for steel tanks categorizing the tank only whether it is anchored or unanchored. In addition, [6, 10] suggest to consider parameters such as H/D ratio and tank fill level. In this case, the fragility parameters are based on the values proposed for tanks with H/D ratio less than 0.7, which are the most compatible for oil farm tanks. Moreover, in case of tank farm, the fragility of the farm will be yielded in accordance with the damage states definition, and as a binomial distribution of k damaged tank of n total tanks in the farm.

4.3. Diesel generator

The diesel generator is used as emergency power-supply in case of external power grid failure. The generator is mostly varying by capacity, vibration isolation, and anchoring. In this case, the backup generator is a diesel generator with a

Capacity of 350 to 750 kVA with unanchored equipment and without vibration isolation. The fragility parameters are based on [4, 20].

4.4. Power grid

The operation of the site is based on the ongoing supply of electric power. In this case, the electric power supply is based on two sources: In routine, the electric power supply to the facility is based on the local electricity distribution networks. in case, of a malfunction or damage to the external electrical path, a generator is placed in the facility to provide a solution until the electricity supply is restored. For this case study, the fragility parameters of the power grid are based on the HAZUS methodology [4].

4.5. Mechanical equipment

For this case study, the fragility parameters for the mechanical equipment are based on HAZUS methodology [4].

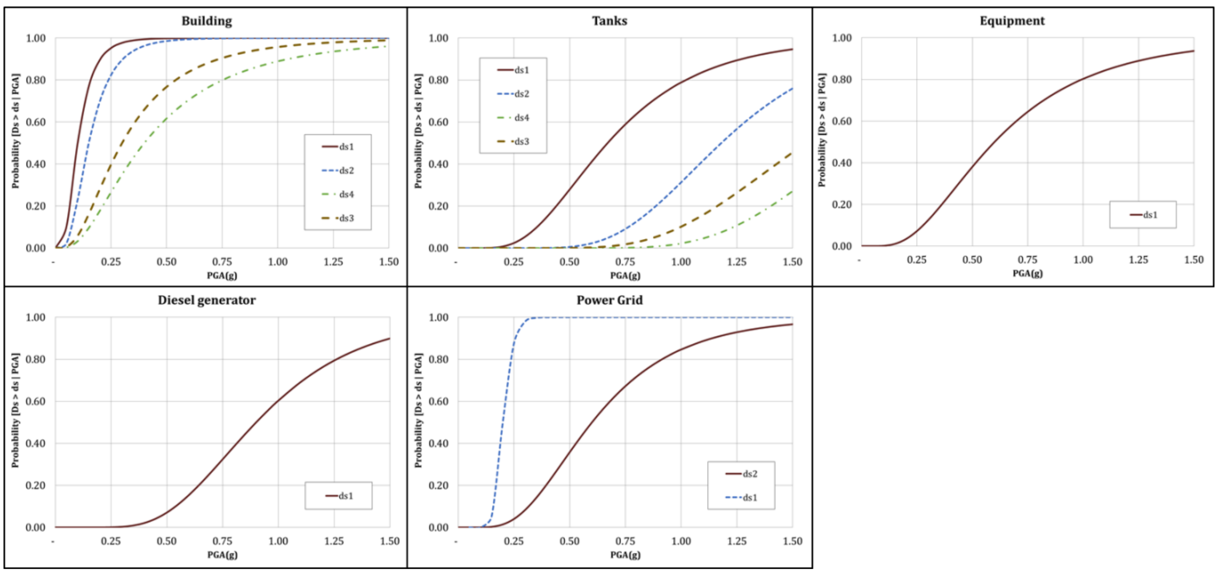

Figure 6 – Fragility curves of the oil tank farm system's sub-components – Case study 2

4.6. Development of the system fragility curve

Based on the fragility parameters of the sub-components and the system's damage state definitions, one can develop a unique fragility curve for each particular system, in the present case, an oil tank farm. The fragility curve is composed of several curves that express the sequential damage states of the system. At the last step of the fragility development, the evaluation of the fragility parameters of each damage state (θ_{ds} and β_{ds}) are derived. Figure 7 below presents the fragility curves of the oil tank farm based on those parameters.

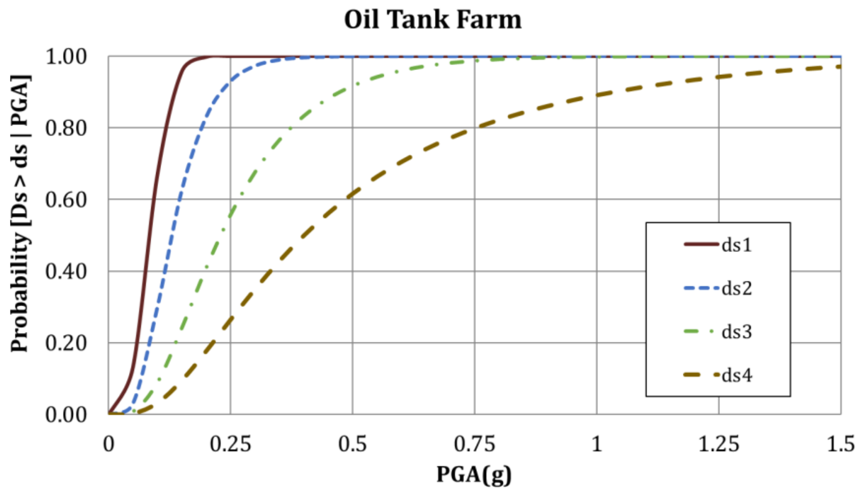

Figure 7 - Fragility curve of an oil tank farm – Case study 2

4.7. Comparison with the literature

A comparison of the results with fragility parameters that are proposed by [4] are presented in Table 2. The differences between the parameters are most likely due to the differences in the definition of the events that attributed to each damage state. It is required to perform further analysis to examine the sensitivity of the scenarios that are defined to each damage state and to associate the scenarios with the various fragility curves.

Table 2 - Comparison of this paper results with fragility parameters that are proposed by (NIBS 2004)

Damage State	**This research**		**NIBS 2004** [4]	
	θ	***β***	***θ***	***β***
Slight/minor	0.10	0.27	0.12	0.55
Moderate	0.15	0.52	0.23	0.55
Extensive	0.30	0.64	0.41	0.55
Complete	0.40	0.74	0.68	0.55

5. Sensitivity Analysis

The proposed methodology is coping with several uncertain parameters that are essential for seismic risk appraisal. The uncertainty of the seismic event is expressed in annual rate of exceedance, and the uncertainty of the damage because of the event is expressed by the fragility curve. The fragility curve process aggregates the parameters of several fragility functions which are mainly based on prior studies. For some sub-components, several sources offer different fragility parameters for the sub-component. In these cases, relying on one of the sources will, in some way, affect the risk curve. Therefore, it is highly important to examine the influence range and the sensitivity of the uncertain parameters. This sensitivity analysis examines the marginal cost of the sub-component median.

The following Tables present examination of the sensitivity of the median to the damage state of each sub-component ($\Delta\theta_{\mathrm{ds}_{sub-component}}$) and the following change on the medians of the tank farm damage states ($\Delta\theta_{\mathrm{ds}_{oil\ farm}}$) by value, the value in brackets expresses the percentage change. The first row represents the original values followed by three levels of changes in the median parameter: 50% reduction, 50% increase, and 100% increase.

Table 3 – Summary of the sensitivity analysis by sub-component. The value in brackets expresses the percentage change.

Sub-component			Oil Tank Farm			
			0.082 (0%)	**0.128 (0%)**	**0.228 (0%)**	**0.4 (0%)**
	Ds_i	Ds_i^*	Ds_1	Ds_2	Ds_3	Ds_4
Building	$Ds_1 = 0.1$	0.05 (-50%)	0.049 (-40%)	0.128 (0%)	0.296 (30%)	0.4 (0%)
		0.15 (50%)	0.1 (22%)	0.128 (0%)	0.296 (30%)	0.4 (0%)
		0.2 (100%)	0.107 (30%)	0.128 (0%)	0.296 (30%)	0.4 (0%)
	$Ds_2 = 0.15$	0.075 (-50%)	0.061 (-26%)	0.073 (-43%)	0.228 (0%)	0.4 (0%)
		0.225 (50%)	0.088 (7%)	0.162 (27%)	0.228 (0%)	0.4 (0%)
		0.3 (100%)	0.089 (9%)	0.183 (43%)	0.228 (0%)	0.4 (0%)
	$Ds_3 = 0.3$	0.15 (-50%)	0.074 (-10%)	0.103 (-20%)	0.138 (-39%)	0.4 (0%)
		0.45 (50%)	0.083 (1%)	0.135 (5%)	0.282 (24%)	0.4 (0%)
		0.6 (100%)	0.083 (1%)	0.137 (7%)	0.315 (38%)	0.4 (0%)
	$Ds_4 = 0.4$	0.2 (-50%)	0.077 (-6%)	0.111 (-13%)	0.159 (-30%)	0.2 (-50%)
		0.6 (50%)	0.082 (0%)	0.132 (3%)	0.259 (14%)	0.596 (49%)
		0.8 (100%)	0.082 (0%)	0.133 (4%)	0.274 (20%)	0.777 (94%)
Tanks	Ds_1 =0.67	0.335 (-50%)	0.081 (-1%)	0.128 (0%)	0.228 (0%)	0.4 (0%)
		1.01 (50%)	0.082 (0%)	0.128 (0%)	0.228 (0%)	0.4 (0%)
		1.34 (100%)	0.082 (0%)	0.128 (0%)	0.228 (0%)	0.4 (0%)
	Ds_2 =1.18	0.59 (-50%)	0.082 (0%)	0.128 (0%)	0.228 (0%)	0.4 (0%)
		1.77 (50%)	0.082 (0%)	0.128 (0%)	0.228 (0%)	0.4 (0%)
		2.36 (100%)	0.082 (0%)	0.128 (0%)	0.228 (0%)	0.4 (0%)
	Ds_3 =1.56	0.78 (-50%)	0.082 (0%)	0.128 (0%)	0.227 (0%)	0.4 (0%)
		2.34 (50%)	0.082 (0%)	0.128 (0%)	0.228 (0%)	0.4 (0%)
		3.12 (100%)	0.082 (0%)	0.128 (0%)	0.228 (0%)	0.4 (0%)
	Ds_4 =1.79	0.9 (-50%)	0.082 (0%)	0.128 (0%)	0.228 (0%)	0.389 (-3%)
		2.685 (50%)	0.082 (0%)	0.128 (0%)	0.228 (0%)	0.4 (0%)
		3.58 (100%)	0.082 (0%)	0.133 (4%)	0.274 (20%)	0.777 (94%)
Generator	$Ds_1 = 0.9$	0.45 (-50%)	0.082 (0%)	0.128 (0%)	0.218 (-4%)	0.4 (0%)
		1.35 (50%)	0.082 (0%)	0.128 (0%)	0.228 (0%)	0.4 (0%)
		1.8 (100%)	0.082 (0%)	0.128 (0%)	0.228 (0%)	0.4 (0%)
Power grid	Ds_1 =0.15	0.075 (-50%)	0.064 (-22%)	0.128 (0%)	0.228 (0%)	0.4 (0%)
		0.225 (50%)	0.083 (1%)	0.128 (0%)	0.228 (0%)	0.4 (0%)
		0.3 (100%)	0.083 (1%)	0.128 (0%)	0.228 (0%)	0.4 (0%)
	Ds_2 =0.6	0.3 (-50%)	0.081 (-1%)	0.125 (-2%)	0.228 (0%)	0.4 (0%)
		0.9 (50%)	0.082 (0%)	0.128 (0%)	0.228 (0%)	0.4 (0%)
		1.2 (100%)	0.082 (0%)	0.128 (0%)	0.228 (0%)	0.4 (0%)
Equipment	Ds_1 =0.60	0.3 (-50%)	0.081 (-1%)	0.123 (-4%)	0.228 (0%)	0.4 (0%)
		0.9 (50%)	0.082 (0%)	0.129 (1%)	0.228 (0%)	0.4 (0%)

		1.2 (100%)	0.082 (0%)	0.129 (1%)	0.228 (0%)	0.4 (0%)

This examination reveals that the most significant sub-component in most cases is the building; the fragility curve parameters of the entire system are most sensitive to inaccuracy in the fragility parameters of the building. However, in most cases the change in the farm medians is much smaller than the change in the sub-components median. Moreover, because of the complexity of the system, an inaccuracy of a single parameter will not significantly affect the risk of the entire system.

6. Conclusion

This paper introduces a probabilistic risk appraisal methodology intended for decision support toolfor priority setting of mitigation strategies based on the seismic risk expectancy of critical infrastructures. The paper presents an implementation of the methodology through two case studies: pumping plant case and an oil tank farm case. The pumping plant case demonstrates the development of a seismic risk function. In this case, the risk expectancy curve reveals that the majority of the risk is concentrated at the low-moderate peak ground accelerations levels. A possible mitigation strategy was examined, and the subsequent reduction of risk was analyzed. It was found that the most effective mitigation strategy can reduce the overall risk expectancy by over 25%. Moreover, this paper focuses on the development of an exclusive fragility curve for a unique system, for these cases in which the generic fragility curves, available in the literature, are insufficient. The implantation of this approach is presented through an oil tank farm case study; in this illustration, the oil tank farm is composed of five main sub-components: building, storage tanks, power grid, backup generator, and mechanical equipment. Subsequently, based on the fragility parameters of the sub-components and the system damage state definition, the fragility curve of the system was yielded. A comparison of the results with fragility parameters that are proposed in the literature reveals that the differences between the parameters are most likely due to the differences in the definition of the events attributed to each damage state. Furthermore, a preliminary sensitivity analysis of the uncertain parameters (median of the damage states of the various sub-components) was performed; it was found that due to the complexity of the system, an inaccuracy of a single parameter, in most cases, will have insignificant effect on the total risk expectancy of the entire system.

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Process Reengineering using Activity Theory and Domain Mapping Matrix Method in Delivering Public Construction Projects

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Abstract

The complexity of modern construction projects has been increasing due to the increased number of design disciplines, stakeholders, process and tools. In public project delivery, these complexities are further increased due to the existence of additional bureaucratic procedures. These decade old processes and the bureaucratic procedures left with dysfunctionalities, redundancies and non-value adding process wastes to the project outcome. This in-turn has a significant adverse knock on effect on the public project delivery in time, cost and quality outcomes. Hence, understanding the existing interactions and its complexity among the project delivery elements such as process, people and deliverables in public project delivery are paramount important to modifying the same to obtain the desired outcome based on the dynamic industry needs. In this proposed research, an example public project delivery department's existing workflow was captured using activity theory. Further, the existence of various people, process, deliverables and their interactions in the project delivery process were identified through an IDEF0 models. The identified project delivery elements and its interactions were then analyzed using a Multi Domain Mapping (MDM) method to evaluate against process dysfunctionalities, redundancies and wastes. In addition, the study also proposed an improved process flow by eliminating the above said discrepancies through a structured business process-reengineering framework. Further, the study validates the proposed framework through expert interview on the modifications made in project delivery elements. The proposed framework will be a guideline/ reference for similar business process reengineering exercise towards a public project delivery process in this region or in a similar context.

Peer-review under responsibility of the scientific committee of the Creative Construction Conference 2019.

Keywords: Process Reengineerin;, Public Project; Multi Domain Mapping Matrix; Activity Theory.

1. Introduction

Modern construction projects delivery methods are complex and multidisciplinary in nature; this demands seamless interactions of various simultaneous processes among different project stakeholders. The simultaneous execution of various project processes poses challenges on its delivery. Further, these projects are also characterized with inefficient project delivery in terms of cost and time[1,2]. Most of these inefficiencies are attributed towards the differing objectives of various stakeholders in contrast with the project outcomes [3]. Further, the decade old bureaucratic processes along with traditional project delivery methods create a complex socio-technical issues while delivering the public projects and inheriting the process wastes and redundancies. This complexity related issues can be attributed from aspects such as the organizational structure, procedures, policies and techniques [3]. Further, these complexities are pulling back the planned flow of the projects and negatively affecting the management and coordination capabilities of projects stakeholders [4]. Understanding the existence of these project complexities and removing the process wastes

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and redundancies is important to improve the project efficiency and performance. Hence, the current study took a government entity called as "SDPW" (named for this manuscript readability purpose only, there is no such name exists), that is responsible of delivering public projects in UAE as the study case. SDPW was formed in 2000 and it is mandated to study, design, implement and maintain government-building projects to improve the public services and infrastructure in a provincial government. In order to maintain and deliver the public building projects, the entity had established three main departments: 1. Chairman Office (CO), 2.Building Projects Department (BPD) and 3.Contract and Tendering Department (CTD). CO is responsible for approving project budget, design and payments. BPD has two sub sections, which are design section and supervision section; it is responsible of designing and supervising the project respectively. CTD is responsible for analysing the tender and preparing contract document. Each department has its own structured processes through which the projects are delivered in stages. Even though, there are enough resources and the existence of a clear and well-defined process flow framework, SDPW is facing challenges such as delay and cost overruns while delivering the public projects. A pilot study was conducted to validate the same; the study took 33 projects among the 136 projects delivered during the past 3 years as a sample. This sample analysis showed that 20 out 33 projects were facing cost overrun and on the other hand, 30 out of 33 projects underwent delay. There might be many reasons attributed towards these project delivery outcomes. In order to investigate the reasons towards these inefficiencies, a follow-up of 12 pilot interviews were conducted with the respective project managers of these affected projects. The interview revealed that there were redundant processes and process wastes which played a significant role on the delay and cost overruns in all those affected projects commonly, it was also been informed that the current pubic project delivery process to manage people, processes and deliverables have dysfunctionalities and inefficiencies. Alleviating the same and improving the public project delivery efficiently is of paramount important. Hence, this paper propose a solution approach for the problem identified through the following sequences. First, the existing SDPW process flow is captured using a simple flow chart. Then, the activity theory was used to capture the interrelated interaction of process people and deliverables of this complex system of public project delivery. These interrelated interactions among various activities were described in a detailed, using IDEF0 model. With the use of the developed IDEF0 model for each of the project stage, an MDM model was generated to visualize the relationship among the various project processes stakeholders and tools. The MDM analysis identify the dysfunctionalities redundancies and process wastes during the project delivery processes. The proposed framework will be a guideline/ reference for someone, who is willing to perform similar business process reengineering exercise for their public project delivery process. The paper has 7 sections, the following section critically review the literatures on the process modelling tools, section 3 explains the adopted study methodology, Section 4, 5 and 6 describe the data manipulation and analysis of current project delivery processes and the proposed reengineered project delivery processes. The summery and discussions are presented in section 7.

2. Literature Review

2.1. Business Process Reengineering

Business process can be defined as collection of activities whose final aim is the production of a specific output that is of value to the customer [5]. Davenport and Short described the business process based on three dimensions; Entity: is where the process is taking place, Objects: the process results is object oriented, Activities: processes can be in different types like managerial, operational etc. [6]. The paper also described BPR as redesign of the processes and workflow between organizations in order to achieve specific goals. Hammer et al., stated that BPR is the way of achieving dramatic improvements in a company's performances in quality, cost, speed etc., by radical redesign of its processes [5] and [7]. BPR has been described as a revolution in business administration in which it renovates the operational processes to improve business performance[8]. Therefore, construction process reengineering can be defined as the redesign of existing processes in order to achieve project success. The advent of modern IT tools further defines the BPR as to efficient automation of complex processes using the IT capabilities. Implementation of BPR is not only limited to the companies that are having bad performance but also the companies which seeks performance enhancements. Hammer and Champy identified three type of companies that are needed to implement BPR: 1.

Company that is facing problems in its performance and its expenses is less than its revenue, 2. Company that are not facing any bad performance but its manager anticipating that problem is nearby to occur, 3. Company that are highly performed but it is looking forward to developing the lead over its competitors [5]. Hence, BPR becomes inevitable, perennial, and iterative exercise at some regular intervals. It is also reported that BPR has advantages in solving problems and improving the internal system in the companies [9]. However, BPR has to be implemented in an accurate manner to ensure its efficiency. Hammer and Champy identified the major activities that an organization has to carry out to properly implementing BPR; Identifying, delineating and modelling the current work flow, then analyse it for deficiencies, after that new process should be proposed and finally the proposed process has to be implemented in terms of new technical terms, organizational role and responsibilities [5].

2.2. Business Process Reengineering Tools

The tools and techniques that can be deployed during various stages to implement the BPR varies on the purposes of the BPR stages. Aguilar-Savén listed various tools and techniques of BPR and classify them according to their use, application, advantages and disadvantages[9]. Further, this has been referred as a guide to the practitioners and academics while choosing the best tool based on their requirements. The RID and Gantt chart techniques are describing the flow of the activities in a matrix based representation. RID shows the role of individuals in each activity while Gant chart shows the duration of the activities, both tools are somehow difficult in the analysis and modification of the existing diagrams [9]. To overcome the challenges of these tools, this research used a combination of tools. The following subsections described the tools used in this study.

2.2.1. Activity Theory

Activity Theory is an approach that mostly used in analysing and understanding complex systems and their interrelated interactions [10]. Activity theory is a framework that aims to beat dysfunctionalities of micro and macro, mental and material, observation and intervention in analysis and redesign of work [11]. It can be used to identify and conceptualize the collaborative activities of project team and as a framework in the delivery process [10,11]. Leont'ev described that activity is composed of subject, objects, actions and operations [12]. A subject is a person or a group engaged in an activity. An object is held by the subject and motivates activity, giving it a specific direction, there is always a need or a desire is standing behind the object. Actions are goal-directed processes that must be undertaken to fulfil the object. They are conscious and different actions may be undertaken to meet the same goal. There are six principles of activity theory stated in the research conducted by Version [13]; the most fundamental and the first principle is the unity of the consciousness and activity "Consciousness" in this expression means the human mind as a whole and is a special component that relates human interaction with its environment [13]. The second principle is object-oriented. This principle specifies the activity theory approach to the environment with which human beings are interacting. This environment consists of entities that combine all kinds of objective features, including the culturally determined ones, which, in turn, determine the way people act on these entities. The third principle is "hierarchical structure of activity." Activity theory differentiates between processes at various levels taking into consideration the objects to which these processes are oriented. The fourth principle according is the internalization/externalization [14]. This principle is describing mechanisms underlying the originating of mental processes. It states that mental processes are derived from external actions through the course of internalization. The fifth principle is mediation. This principle states that human activity is mediated by external and internal number of tools. The last principle is the principle of development. It gives an opportunity to conduct thorough scientific analysis of complex phenomena while avoiding mechanistic oversimplifications [11]. Activity theory showed its effectiveness in solving problems that related to lack of coordination and communication between stakeholders in an activity system by analysing and modelling of the contradiction in the system [15]. Further this theory provides framework for guiding the system through process changes by dealing with contradictions and disturbances within and between the constitutes of the system, and enabling the adaption of new situations [16,17].

2.2.2. Integration Definition for Function Modeling (IDEF0)

Integration Definition for Function Modeling (IDEF0) models are consider as the most commonly used tools by engineers to capture and analyze the complexity of a system and study the relationship of system component [18]. IDEF0 has been developed as a standard representation of an organized activity and processes [19]. IDEF0 models are characterized by its ease in understanding and its versatility towards its modification capabilities, it is well defined and structured and it can be used for analyzing up to an in depth details [18]. IDEF0 has a notational construct called ICOM (Input-Control-Output-Mechanism). IDEF0 supports process modelling by decomposing higher-level ICOMs into more detailed models that depict the hierarchical decomposition of activities [20].

2.2.3. Multiple Domain Matrix (MDM)

Design Structure Matrix (DSM) tool is commonly used to analyse and represent complex system and especially used for decomposition and integration of systems[21]. The advantages of DSM have increased its usage in different sector and purposes including product development, project planning, project management, systems engineering, and organization design [21]. The DSM approach entails the decomposition of a system into its constituents at various hierarchical levels, identification of the relationships among the elements, analysis to understand the system's behavior [22]. The extension of the DSM is the multi-domain matrix (MDM). It is a rectangular matrix mapping between different DSM domains [23]. MDM has the ability to represent numerous networks and capture more than one relationship types at the same time [24]. MDM showed its effectiveness and advantageous as a process modeling tool through its analysis capability [23,24]. It has a capability to capture the system complexity in a most realistic way [25]. Hence, to identify and capture the interrelationships among the various domains through MDM in this study.

2.3. Study Case

This study takes SDPW as a case; hierarchal structure of SDPW is shown in Fig. 1. The hierarchal structure shows that there is a manager for both CTD and BPD. Furthermore, BPD has two sections, which are; Design and Supervision, each section has its own head. The employees in design section consist of Architecture Engineers, Mechanical-Electrical-Plumbing (MEP) Engineers and Draftsmen. In supervision section there are Supervision engineers and MEP engineers, while in the CTD there are contract and MEP engineers and quantity survivor. SDPW business process is complex as it involved many stakeholders and its process flow had been developed decades back before the advent of the modern tools such as IT applications and management.

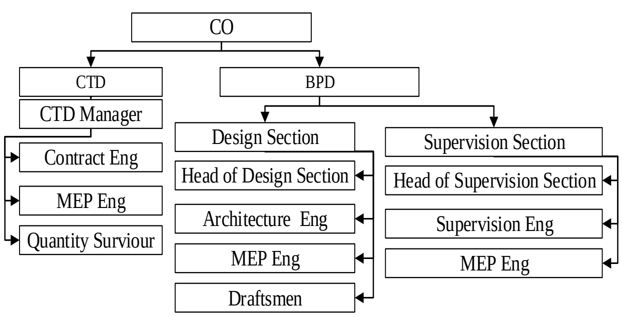

Fig. 1. SDPW Hierarchal Structure

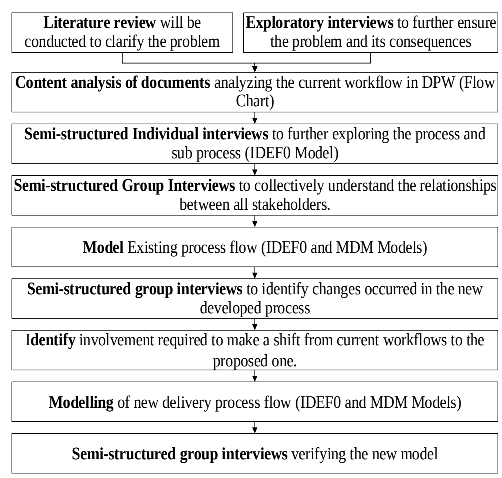

Fig. 2. Research Method

3. Adopted Research Method

Fig.2. illustrates the steps adopted in this research. As the first step, the study sampled 33 numbers of recent projects to validate the need for the study followed by the extensive literature review to understand and explore the subject area. Pilot interviews were conducted to extracts the information such as the organizational structure, functions, rules etc., about different departments in SDPW. This further assist to assess the current state of public project delivery processes. The pilot interviews were conducted with the managers of the three departments overlooking the public project delivery in SDPW. The existing process flow was captured and analysed through series of individual and group

interviews with the relevant stakeholders. There were 12 individual interviews representing all stakeholders and the group interview was conducted with the group consist of head of design section, head of supervision section, 2 contract engineer, a quantity survivor, a supervision engineer, an architecture engineer and 3 MEP engineers; one from CTD department and one from each section in BPD department. The number of the individuals participated in group study was within the limit of study group stated in the research conducted by Stewart et al [27]. The existing process flow has been modelled using IDEF0 method. The analysis of the existing process is done through DSM/MDM method. After analysing the processes to remove the dysfunctionality and non–value adding project elements, group interview was conducted to identify the changes occurred. Then the modification of the existing project elements to alleviate the dysfunctionalities, redundancies and wastes are capture in the modified MDM and IDEF0 models. Validation of the proposed project delivery framework was evaluated by the group interviews consists of 12 respondents. Due to the limitations on the paper length only the CTD process is been explained in the following sections to demonstrate the proposed process reengineering method.

4. Analysis of Existing Process Flow

Based on the developed process flow chart and the activity theory representation for each of the project delivery processes steps, the IDEF0 model was created. The validity of the IDEF0 model was ascertained through a series of structured interviews about all these system components by the relevant stakeholders in the CTD department. Fig. 3 shows the IDEF0 model of the CTD department system components.

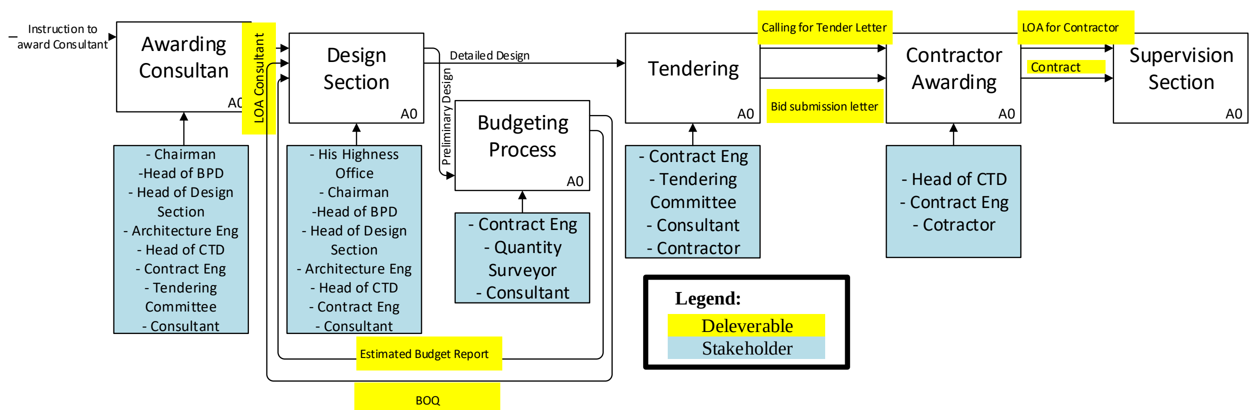

Fig. 3. IDEF0 for Existing Process Flow

The model shows that the CTD department is responsible for 7 deliverables during their project delivery stage. There are 11 different stakeholders involved in 11 sub-processes to deliver these 7 deliverables. It is also showed that the process of CTD is interrelated with the process in BPD design section and BPD deliverables. To further analyze these captured processes and identifying the relationship between the processes, deliverables and stakeholders, an MDM model has been developed. MDM captured the existence and the type of relationships between deliverables – stakeholders, deliverable-processes, processes- stakeholder. The existence of relationship was categorized as; 0 = no relation, 1= procedural relation and 2 = logical relation. The procedural relationship are to exercise the bureaucratic authority to the subordinate. However the logical relationship are to be observed without compromise to achieve the desired project outcome. To determine the same, a set of standard 5 questions have been asked to the respondents based on which, the existence and type of the relationship had been determined. The question asked to the respondents are as follows; 1. Is this deliverable /stakeholder necessary to perform this task/to proceed next? 2. Is this procedural / logical relationship? 3. How can this deliverable /stakeholder be managed? 4. Can the sequence of this deliverable /stakeholder be changed? 5. What will happen if this deliverable is deleted? and/or the stakeholder not involved? Furthermore, the MDM model also captured the repetitions or the delay incurred by each stakeholder against each of the processes and there by the deliverables as shown in the red diagonal cells in Fig.4.

Legend	Logical Need = 2 Procederal Need = 1 No relation= 0
Sum of repetition in each process	0 1 2 3 4 5 6 7 8 9 10 Low to High Probability of Repetion

			Deliverables							Stakeholder											Process										
			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29
			LOA for Consultant	BOQ	Estimated Budget	Calling for tender letter	Bid Submission	LOA for contractor	Contract	His Highness office	Chairman	Head of Building Dept	Head of Design Section	Design Archt Eng	head of Contract dept	Contract Eng	Quantity Surviour	Tendering Committee	Consultant	Contractor	Prepare BOQ	Prepare Budget Estimation Report	Prepare Internal Memo for Budget Estimation	Prepare tender documents	Prepare letter for consultant to start	Prepare Internal Memo for suggested contractors	prepare letter for invitation for bid	prepare reports for bidding results	prepare intrenal Memo for bidding result	prepare LOA for contractor	prepare the contract
Deliverables	1	LOA for Consultant																													
	2	BOQ																													
	3	Estimated Budget Report																													
	4	Calling for tender letter																													
	5	Bid Submission																													
	6	LOA for contractor																													
	7	Contract																													
Stakeholders	8	His Highness office	0	0	1	0	0	0	0												0	0	0	0	0	0	0	0	0	0	0
	9	Chairman	2	0	2	0	0	2	1												0	5	7	0	2	2	2	2	7	2	2
	10	Head of Building Dept	1	0	1	1	1	0	0												0	4	4	0	0	0	0	0	0	0	0
	11	Head of Design Section	1	0	1	1	1	0	0												0	2	2	0	0	0	0	0	0	0	0
	12	Design Archt Eng	1	0	1	1	1	0	0												0	0	0	0	0	0	0	0	0	0	0
	13	head of Contract dept	2	0	2	1	1	2	2												2	3	3	0	3	3	3	3	1	3	3
	14	Contract Eng	2	2	2	2	2	2	2												3	0	0	0	0	0	0	0	0	0	0
	15	Quantity Surviour	0	2	0	0	0	0	0												0	0	0	0	0	0	0	0	0	0	0
	16	Tendering Committee	2	0	0	2	2	0	0												0	0	0	0	0	0	0	0	0	0	0
	17	Consultant	2	2	2	2	2	0	0												0	0	0	0	0	0	0	0	0	0	0
	18	Contractor	0	0	0	0	2	2	2												0	0	0	0	0	0	0	0	0	0	0
Process	19	Prepare BOQ	2	2	0	1	0	1	1	0	0	0	0	0	0	2	2	0	2	0	5										
	20	Prepare Budget Estimation Report	2	0	2	0	0	0	0	0	0	1	1	1	1	2	0	0	0	0	2	14									
	21	Prepare Internal Memo for Budget Estimation Report	0	0	2	2	0	0	0	0	0	1	1	1	1	2	0	0	0	0	2	2	16								
	22	Prepare tender documents	0	0	0	2	0	0	0	0	0	0	0	0	0	2	0	0	2	0	2	2	0	0							
	23	Prepare letter for consultant to start tendering process	2	0	2	2	0	0	0	0	0	0	0	0	1	2	0	0	0	0	2	2	0	2	5						
	24	Prepare Internal Memo for suggested contractors	2	2	0	0	2	0	0	0	0	0	0	0	2	2	0	2	0	0	0	0	0	0	0	5					
	25	prepare letter for invitation for bid	2	0	2	0	2	0	0	0	0	0	0	0	1	2	0	0	2	0	2	1	0	0	0	0	5				
	26	prepare reports for bidding results	2	0	0	0	2	0	0	0	0	0	0	0	2	2	0	2	2	0	0	2	0	0	0	0	2	5			
	27	prepare intrenal Memo for bidding result	0	0	0	0	2	0	0	0	0	0	0	0	2	2	0	0	0	0	0	0	0	0	0	0	2	2	8		
	28	prepare LOA for contractor	2	2	0	2	2	2	1	0	1	0	0	0	2	2	0	0	0	0	1	1	1	1	2	0	1	2	2	5	
	29	prepare the contract	0	0	0	0	0	2	2	0	1	0	0	0	2	2	0	0	2	0	1	1	1	1	2	2	1	2	2	1	5

Fig. 4. MDM model current- status

5. Identification of Process Waste, Redundancy and Dysfunctionality.

The analysis of the MDM started with the Process DSM as shown in the figure 4. The diagonal represents the repetition of the processes by various stakeholders captured in the DMM of Stakeholders Vs Processes. The most repetition and there by the delay was recorded in the processes called "preparing budget estimate and prepare internal memo to budget estimation" as shown in cells (read as Row and Colum numbers respectively) (20, 20) and (21, 21) respectively. The BPD manager and head of design section are responsible stakeholders for the same, since both stakeholders are external parties (from outside of the CTD department) and causing the processes to be repeated 6 times. By examining the existence and the type of the interrelationships between these stakeholders and the process, it is clear that there exists a relationship and is considered as a procedural relationship as shown in cells (20, 10), (20, 11), (21, 10) and (21, 11) (which is part of a bureaucratic setup made while the SDPW was established). However, neither the process nor the stakeholders adds value to the processes and its deliverables, except as an another bureaucratic reporting system. Hence, these stakeholders and their relevant processes should be removed from the process loop to avoid delay. Similarly, all the processes, its relationship with the stakeholder and its deliverables were investigated against the existence of the process inefficiencies such as process wastes, redundancies and dysfunctionalities. These identified inefficiencies were then reengineered through changing the process, policies and the responsibilities.

6. Reengineered Process Flow

Reengineering the processes as described in the previous section helped to reduce the number of repetition in the process. Moreover, by changing the policy in signing the Letter of Award (LOA) and contract for the contractor by giving the CTD manager the authorization to sign instead of the chairman would help in reducing the redundancies and time delay. The new MDM model was created based on the elimination of the process waste, redundancies and dysfunctionality in CTD department as shown in Fig.5. The same was highlighted with green shade in the cells. Though the deliverables of the modified and the existing processes are same, the stakeholders and their redundancies in terms of procedural process wastes have been removed.

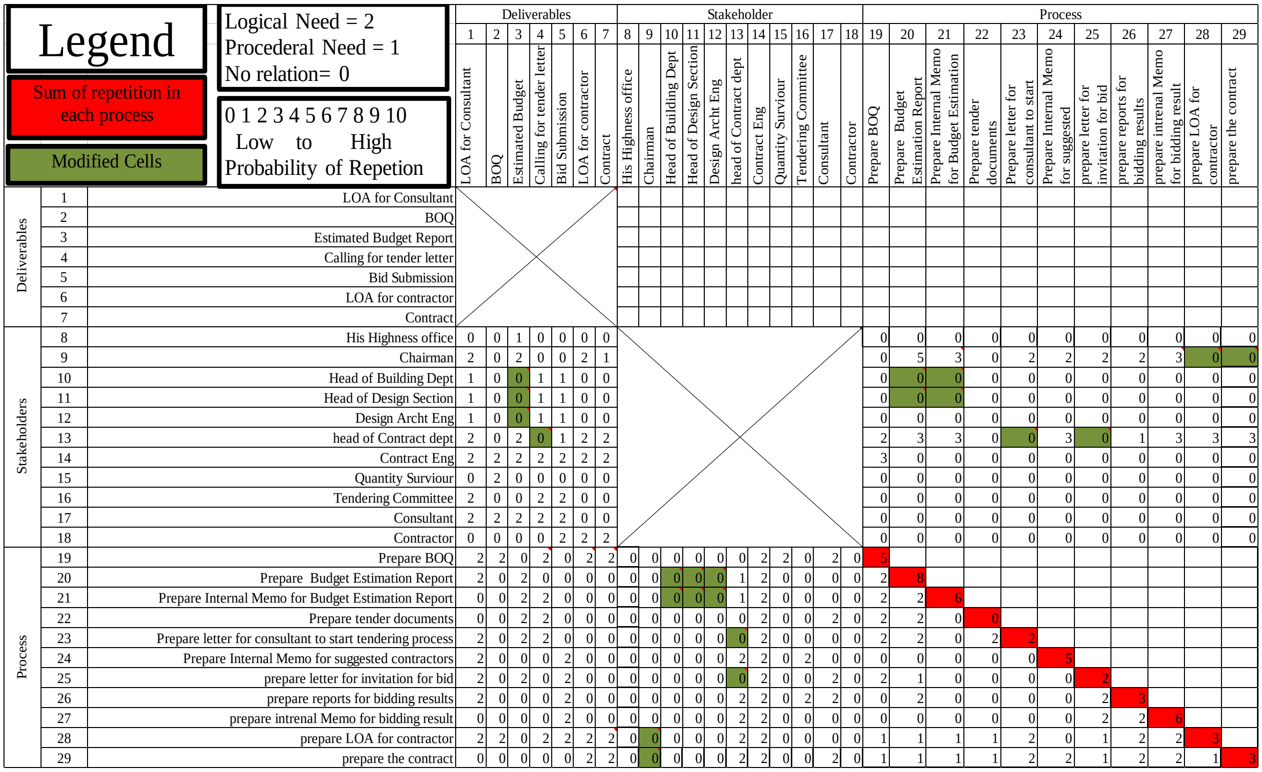

Fig. 5. MDM model after reengineered process

There were 10 procedural relationships which were adding no value to the project delivery were removed as mentioned in the shaded Process Vs Stakeholder DMM. As the result, the process repetitions and the overall time taken to accomplish the project delivery had been realized. Table 1 summarize the total number of repetition occur in each process in CTD department before and after the reengineering process. It shows that the total number of repetition has been reduced from 73 to 43, which will help in reducing the delay in the CTD department.

Table 1. No of repetition before and after reengineering the processes

Process		Prepare BOQ	Prepare Budget Estimation Report	Prepare Internal Memo for Budget Estimation Report	Prepare letter for consultant to start tendering process	Prepare Internal Memo for suggested contractors	Prepare letter for invitation for bid	Prepare reports for bidding results	Prepare internal Memo for bidding result	Prepare LOA for contractor	Prepare the contract	Total
No of repetition	Before	5	14	16	5	5	5	5	8	5	5	73
	After	5	8	6	2	5	2	3	6	3	3	43

7. Summary and Discussion

The process reengineering of any organization is inevitable due to the competitiveness as well as to improve the efficiency of the project delivery. Most of the public project delivery organizations are not performing the process reengineering regularly and there by left with bureaucratic procedures that does not match with the advancement of the modern industry. This paper attempted to capture the existing project delivery processes through a structured process reengineering procedure and demonstrated its applicability in delivering the public projects. The identification and the removal of process wastes, dysfunctionalities and redundancies are developed through a structured interview procedure to ascertain the facts. The obtained responses and the data were further utilized through a combination of process modelling tools, which are relevant to the study context. The paper used the activity theory to capture the in depth relationships among the various project system components such as the processes, stakeholders and the deliverables. The IDEF0 is used to identify the interactions of various processes along with its responsible stakeholders and their deliverables towards the successful project delivery. The generated IDEF0's help the development of MDM's to capture the existence of the relationships and identification of procedural/logical relationships. The combination of the above tools demonstrates a thorough understanding of the project delivery processes in SDPW. The procedural relationships are then qualified as value adding and non-value adding relationships. The procedural relationship which has no values other than the age-old bureaucratic procedure are considered as wastes and are removed. Further, the study validates the proposed methodology through 12 expert interviews and compared the before and after effect theoretically. The comparison shows that there are potential 30 revisions, which can be avoided and there by the delay can be mitigated. In addition, the results showed that the redundancy in this process has been reduced by eliminating the procedural relationships between the stakeholders and the deliverables and there by accelerating the internal processes. However, the actual implementation of the proposed reengineered procedure is yet to be tested due to the time constraints as well as the delayed approval for the procedural change by the competent authority. The proposed framework will be a guideline/ reference for similar business process reengineering exercise towards a public project delivery process in this region or in a similar context.

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Professionals View on Drivers That Enhance the Development of Remanufacturing in Nigeria

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Abstract

This study seeks to determine the drivers of remanufacturing from the professional's view. The methodology used for this study is the quantitative methodology, a mean item score and a normality test to determine their views and finally used the Mann-Whitney test to determine the views of the professionals. Findings from this research method revealed that there was no significant difference in the way; professionals viewed the drivers of remanufacturing. Further discussed was the implication of the findings, which revealed that the major driver of remanufacturing in Nigeria is the creation of job opportunities, which is vital as Nigeria is presently grappling with a high unemployment rate. Finally, it was concluded with the role remanufacturing will aid with the high unemployment in Nigeria.

Keywords: Type your keywords here, separated by semicolons ;

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1. Main text

Remanufacturing is defined as an industrialised process where parts described as cores which have reached their end of life are restored to useful life or almost new [1]. Steps are taken to restore the End of life products namely; inspection, disassembly, part replacement/refurbishment, cleaning, reassembly and testing to ensure the standard desired for remanufacturing is met [2]. A good knowledge of drivers is very necessary in order to develop appropriate strategies and policies for the development of remanufacturing in Nigeria. Studies carried out by Cunha et al (2011)[3] revealed that End of life regulations, increasing reusability, economic viability, OEM remanufacturing, new markets, product service systems, remanufacturing inside users, new demand, green labelling and certifying by association are some of the drivers of remanufacturing that could help develop and grow the remanufacturing industry. Further supported was studies carried out by [4] for drivers of remanufacturing in Greece revealed that customer service, green image, competition, profitability and legislation are some of the drivers by which remanufacturing is practised in Greece. In Finland [5] found that the drivers for remanufacturing include profitability, reduction of environmental impact, existing demand for remanufactured products, compliance with legislation, third parties remanufacturing products. In Sweden, [6] concluded the results of the research on drivers of remanufacturing include improving turnover, competition,

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strategic advantage, green image, asset production, environmental legislation, and ecological motivation. The aim of this study is to identify the drivers of remanufacturing in Nigeria from the professionals' view.

2. Methodology

Respondents were requested to indicate the degree of importance of each of the drivers of remanufacturing that play a role in the transition of a green economy based on a five-point Likert scale (strongly agree = 5, agree = 4, neutral, = 3, disagree = 2, strongly disagree = 1). Ninety-eight complete questionnaires were received signifying an 81% response rate.

The demographics of the respondents indicated that the majority of the respondents who participated in this survey were of the age range from (26-30) years to (31-35) years and had a work experience of (2-5) years and (6-10) years in the manufacturing industry.

Two statistical analysis were carried out namely descriptive statistics in the mould of (mean item score) and factor analysis. The mean item score was used to find the importance of the variables. Whilst factor analysis was used in establishing which of the variables could be measuring the same underlying effect. The procedure, findings and relevant discussion follow.

2.1. Presentation of the Findings

Factor analysis was employed to establish which of the variables could be measuring aspects of the same underlying dimensions. Factor analysis is useful for identifying clusters of related variables and thus ideal for reducing a large number of variables into a more easily understood framework [7]. Fig.1 presents the scree plot result. Average communality of the variables after extraction is as shown below; the Kaizer-Meyer-Olkin (KMO) measure of sampling adequacy achieved a high value of 0,833; the Bartlett test of sphericity was also significant suggests that the population matrix was not an identity matrix. Thus, the necessary tests in respect to the adequacy of the sample size were favourable for the factor analysis to proceed. Cronbach's alpha of 0,867 suggested the reliability of the study instrument used was good.

Table 1. Communalities

An example of a column heading	Initial	Extraction
C1.2	0.428	0.674
C2.2	0.315	0.240
C2.3	0.435	0.269
C2.4	0.377	0.434
C2.5	0.417	0.735
C3.1	0.563	0.630
C3.2	0.530	0.503
C3.3	0.454	0.385
C4.2	0.405	0.377
C4.3	0.537	0.517
C4.4	0.366	0.377
C5.1	0.318	0.277
C5.2	0.321	0.269
C5.3	0.439	0.489
C5.4	0.511	0.616
C5.5	0.522	0.573

C5.6	0.410	0.382
C5.7	0.587	0.602
C5.9	0.455	0.430
C5.10	0.557	0.562

Table 2: KMO and Bartlett's Test

Kaiser-Meyer-Olkin Measure of Sampling Adequacy		
Bartlett's Test of Sphericity	Approx. Chi-Square	890.988
	df	253
	Sig.	0.000

The data was subjected to principal component analysis (with varimax rotation). The eigenvalue and factor loading were set at conventional high values of 1,0 and 0,5 respectively. As shown in table 3, six components with eigenvalues greater than 1. 00 were extracted using the factor loading of 0,5 as the cut-off point (see also scree plot in Fig 1). The total variance (see table 3) explained by each component extracted is as follows; factor 1 (32,925), component 2 (9,041), component 3 (6,970), component 4 (6,191), component 5 (5,040) and component 6 (4,854). Thus, the final statistics of the principal component analysis and the components extracted accounted for approximately 65% of the total cumulative variance.

Based on the examination of the inherent relationships among the variables under each component, the following interpretation was made component 1 was termed *Manufacturers attitude towards achieving green economy*; component 2 was termed *policies to drive remanufacturing*; component 3 was termed *benefits of driving remanufacturing*; and component 4 was termed *response to driving remanufacturing*; component 5 was termed *manufacturers drive to practise remanufacturing* lastly component 6 was termed *economic benefits of remanufacturing* These names were derived from the components by observation of the components and how closely related the variables are using the highest loading factor.

Normality test were performed on the compared groups to determine whether the y was normally distributed or not normally distributed. The cut-off significance for the normality tests used in this study was 0.05. The Kolmogorov-Smirnov statistic results would be used if the sample size were 50 and above. If the sample size is below 50, t h e Shapiro-Wilk statistics would be used.

In order to test whether there is a difference between the groupings, it is necessary to identify the null hypothesis and the alternative hypothesis.

H_0: Normally distributed

There is no difference between the groups

H_1: Not normally distributed

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There is a difference between groups.

Conditions required to confirm if the variables are normally distributed or not normally distributed are: If P-value is greater 0.05. Do not reject H0 (accept H0) (Normally distributed) If P-value is less than 0.05. Reject H0 (accept H1) (Not normally distributed).

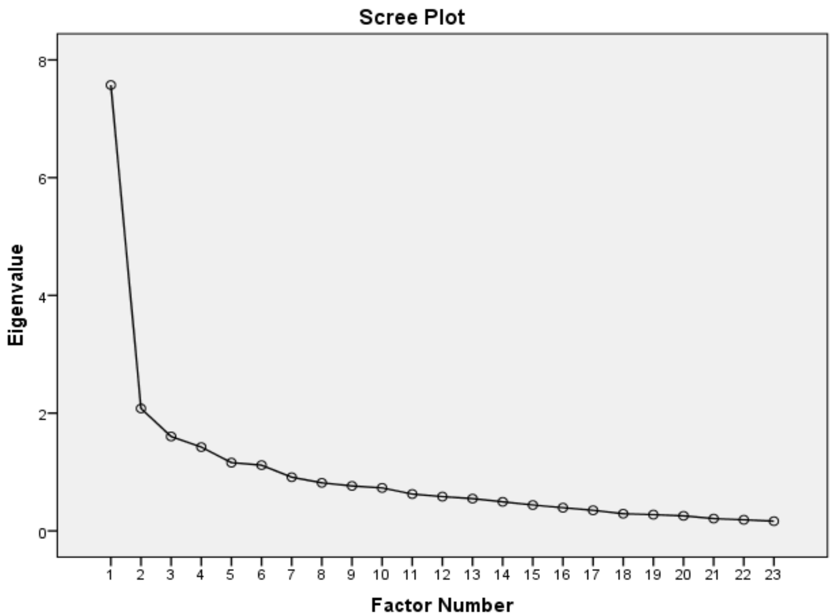

Table 3: Total Variance Explained

Factor	Initial Eigenvalues			Extraction Sums of Squared Loadings			Rotation Sums of Squared Loadings		
	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %
1	**7.573**	32.925	32.925	7.139	31.039	31.039	3.322	14.443	14.443
2	**2.079**	9.041	41.966	1.620	7.045	38.084	2.500	10.867	25.311
3	**1.603**	6.970	48.936	1.119	4.864	42.948	2.133	9.274	34.585
4	**1.424**	6.191	55.127	.960	4.176	47.124	1.968	8.555	43.140
5	**1.159**	5.040	60.167	.663	2.882	50.006	1.384	6.016	49.156
6	**1.117**	4.854	**65.021**	.646	2.807	52.813	.841	3.657	**52.813**
7	.912	3.967	68.989						
8	.816	3.549	72.538						
9	.765	3.324	75.862						
10	.730	3.176	79.038						
11	.626	2.721	81.759						
12	[illegible]	[illegible]	[illegible]						

13	.548	2.382	86.674
14	.494	2.147	88.821
15	.440	1.912	90.732
16	.394	1.714	92.446
17	.350	1.522	93.968
18	.292	1.269	95.237
19	.276	1.199	96.436
20	.256	1.115	97.551
21	.209	.909	98.460
22	.189	.821	99.282
23	.165	.718	100.000

Extraction Method: Principal Axis Factoring

The normality test for *manufacturers' attitude towards achieving green economy* showed that the p-test for less than five years and five years or more indicated that it is less than 0.05. Hence H0 (Null hypothesis) was rejected and H1 (Alternative hypothesis) was accepted. Therefore, it is not normally distributed. **Conclusion**: The null hypothesis was rejected. Thus, there is a difference between the groups

On how they view manufacturers' attitude towards achieving a green economy. Next, the normality test for policies to drive remanufacturing showed that the p-test for less than five years and five years or more indicated that it is less than 0.05. Hence H0 (Null hypothesis) was rejected and H1 (Alternative hypothesis) was accepted. Therefore, it is not normally distributed. **Conclusion**: The null hypothesis was rejected. Thus, there is a difference between the groups on how they view policies to drive remanufacturing.

Secondly, the normality test for benefits of driving remanufacturing showed that the p-test for less than five years and five years or more indicated that it is less than 0.05. Hence H0 (Null hypothesis) was rejected and H1 (Alternative h hypothesis) was accepted. Therefore, it is not normally distributed. **Conclusion**: The null hypothesis was rejected. Thus, there is a difference between the groups on how they view the benefits of driving remanufacturing.

Thirdly, the normality test for response to driving remanufacturing showed that the p-test, for less than five years and five years or more indicated that it is less than 0.05. Hence H0 (Null hypothesis) was rejected and H1 (Alternative hypothesis) was accepted. Therefore, it is not normally distributed. **Conclusion**: The null hypothesis was rejected. Thus, there is a difference between the groups on how they view the response to driving remanufacturing.

In addition, the normality test for manufacturers driver to remanufacturing showed that the p- test for less than five years and five years or more indicated that it is less than 0.05. Hence H0 (Null hypothesis) was rejected and H1 (Alternative hypothesis) was accepted. Therefore, it is not normally distributed. **Conclusion**: The null hypothesis was rejected. Thus, there is a difference between the groups on how they view the manufacturers' drivers to practice remanufacturing.

Lastly, the normality test for economic benefits showed that the p-test for less than five years and five years or more indicated that it is less than 0.05. Hence H0 (Null hypothesis) was rejected and H1 (Alternative hypothesis) was accepted. Therefore, it is not normally distributed. **Conclusion:** The null hypothesis was rejected. Thus, there is a difference between the groups on how they view the economic benefits.

The Man-Whitney test is as shown below;

No significant differences in the manufacturers' attitude towards achieving green economy between less than five years (MD = 4.63, n = 52), and five years or more (MD = 4.75, n = 42), (U = 1009.500, z = -1.339 p = 0.181);

No significant differences in the policies to drive remanufacturing between less than five years (MD = 4.55, n = 52), and five years or more (MD = 4.40, n = 42), (U = 1103.000, z = -0.685, p = 0.493);

No significant differences in the benefits of driving remanufacturing between less than five years (MD = 4.75, n = 52), and five years or more (MD = 4.75, n = 42), (U = 937.500, z = - 1.860 p = 0.063);

No significant differences in the response to driving remanufacturing between less than five years (MD = 4.00, n = 52), and five years or more (MD = 4.25, n = 42), (U = 1071.000, z = - 1.024 p = 0.306);

No significant differences in the manufacturers' drivers to practise remanufacturing between less than five years (MD = 5.00, n = 52), and five years or more (MD = 5.00, n = 42), (U = 1071.000, z = -1.024 p = 0.306);

No significant differences in the economic benefits between less than five years (MD = 5.00, n = 52), and five years or more (MD = 4.50, n = 42), (U = 1100.000, z = -.787 p = 0.431).

3. Discussion of Results

Component 1: Manufacturers attitude towards achieving green economy

The eight extracted barriers of remanufacturing for component 1 were implementation of responsible consumption with (67,7%), achieving a zero landfill reduction with (64,1%), implementation of proper waste disposal of all products and services with (63,9%), achieving a low carbon footprint with (56,6%), multiple product lifecycles with (54,1%), reduction of greenhouse gas emission with (50,9%), prolong life cycle with (46,3%) and remanufactured goods can be sold as new with (42,4%). This cluster accounted for 32, 93% of the variance (see table 6). These criteria share a common link to as manufacturers' attitude towards achieving the green economy. *Achieving a zero-landfill reduction* as seen by Fuji Xerox is an example of a company which achieved zero landfills after Xerox adopted remanufacturing in the 1980s. Xerox achieved zero landfills in Japan in 2000. By employing a closed loop supply chain whereby, the products are recovered via customer take back policy which is then sent to the remanufacturing plant [8]. *Reduction of carbon footprint* is another driver for remanufacturing. In 2005 Caterpillar Global Remanufacturing Operation collected and reused 43 million tonnes of core material, thereby preventing 52 million tonnes of CO_2 emission into the ecosystem [9]. In comparison to other forms of product recovery management, remanufacturing of products will retain all the value [10] functional characteristics, *multiply the lifecycle of the product*, so potentially it has a high level of sustainability and considered as the best way of recovering product' (BWPR).

Component 2: policies to drive remanufacturing

The five extracted barriers of remanufacturing for component 2 were the implementation of initiatives for conservation environment with (72,8%), new market development opportunities (71,3%), pollution control measures with (58,7%), broaden product market research with (50,0%) and product warranty is assured (45,8%). This cluster accounted for (9,04%). Subsequently, this component was labelled policies to drive. Studies have shown that one of the major drivers for remanufacturing is the involvement of government in developing policies to encourage remanufacturing as seen by countries like China, USA. Remanufacturing can be favourable to manufacturers as they seek to broaden their market in search of consumers who then cannot pay for the high cost of new products [11]. According to [12], components used for remanufacturing process are either from the same or from other products. This reduces the use of new components, saves resources, materials, energy and other inputs. Other economic drivers are the assured warranty, life expectancy as good as new, high- quality products, and competitive price which can lead to new market development opportunities as remanufacturers target a specific market audience.

Component 3: Benefits of driving remanufacturing

The four extracted barriers of remanufacturing for component 3 were the creation of job opportunities (71,2%), conservation of natural resources with (56,8%), improve profitability

(51,7%), commitment to maintain environmental balance (44,6%). This cluster accounted for 6, 97%. Subsequently, this component was labelled *benefits of driving remanufacturing.* Sale on remanufactured products can give profit margins as high as 40 percent [13] thus leading to *improve profitability*. Remanufacturing plays a major role in the society as a whole [13]. Products returned are always an economically feasible option (technical and physical upgrade) simultaneously benefiting the society by providing skills in terms of *Job creation* [14]. Ozer (2012)[15] stated that remanufacturing of products is a means of creating profit for the organisation and at the same time brings about benefits to the environment. This benefit brings about a commitment to maintain environmental balance.

Component 4: Response to driving remanufacturing]

For component four, four drivers were extracted. Which were; adequate and timely response to environmental impact with (73,9%), targets and reporting for environmental performance with (67,1%), the creation of a niche market with (56,8%) and portraying of green image organisation with (54,6%). Portraying of a green image by the organisation is the reason why remanufacturing is adopted by the organisation [16].

Component 5: manufacturers drive to practise remanufacturing.

For component five, one driver was extracted. Which were lower production costs with (66,4%) is Significant lower input cost is an economic driver of remanufacturing since cores used in remanufacturing of products are reused [17].

Component 6: Economic Benefits of remanufacturing

For economic six, one driver was extracted. Which were original state of the product is retained with (35,5%)

Discussion of the Mann-Whitney test

From the Mann-Whitney test, the working experience was also compared to see the distribution regarding manufacturers' attitude to green manufacturing against working experience (comparing less than five years and five years and more). Results showed that there was no significant difference between less than five years working experience and five years and more working experience (U=1009.500, z= -1.339, p =0.181). Secondly, comparison of policies to drive remanufacturing against work experience (less than 5 years against five years and more) showed that there was no significant difference (U=997.000, z= -0.028, p =0.978). Thirdly, Comparison of benefits of driving remanufacturing against work experience (less than 5yrs and 5yrs and more) revealed that there was there was no significant difference (U=1103.000, z= -0.685, p =0.493). Furthermore, comparison of response to driving remanufacturing against work experience (less than 5yrs and 5yrs and more) revealed that there was no significant difference (U=937.500, z= -1.860, p =0.063). comparison of manufacturers' drivers to practice remanufacturing against work experience (less than 5yrs and 5yrs and more) showed that there was no significant difference (U=1071.000, z= -1.024, p =0.306). Finally, Comparison of economic benefits against working experience showed that there was no significant difference (U=1100.000, z= -0.787, p =0.431).

3.1. Findings

The empirical finding of this study is consistent with the findings of [18] who revealed that one of the drivers of remanufacturing is its ability to create job opportunities Following drivers for remanufacturing is the achieving of low carbon footprints which is consistent with the study carried out by the Caterpillar Global Remanufacturing Operation which collected and reused 43 million tonnes of core material and prevented 52 million tonnes of Co2 emission inflowing into the ecosystem [19] The reduction of GHG emission is consistent with the study carried out by APRA. The process of remanufacturing has been shown to conserve energy to the sum of trillions of British Thermal Units (BTUs) each year. Thus, remanufacturing lessens the amount of greenhouse emission 20]. A comparison test was carried out to examine whether biographic play a significant role in the way the respondents viewed this research question and it was discovered that biographic doe s not play a role in all groups compared were of the same opinion on the drivers of remanufacturing.

3.2. Implications of result

From the above findings, it is evident that the major driver of remanufacturing in Nigeria is the creation of job opportunities which is vital as Nigeria is presently grappling with a high unemployment rate. Just as the world is struggling with the problem of carbon footprints, so also is Nigeria, hence the drive for the reduction of carbon footprint. Remanufacturing would be a driver as it seeks to reduce the carbon footprint. Furthermore, as Nigeria seeks to transition to a green economy, it is of importance that greenhouse gas emission is reduced, thereby increasing the importance of remanufacturing in its quest, to transition to a green economy. Achieving a zero-landfill reduction is one of the important drivers of remanufacturing as achieving of a zero landfill makes cores available for remanufacturing, thereby leading to an improvement in profitability for remanufacturers.

4. Conclusion

From the primary data, results have shown that creation of job opportunities is seen as a major driver for the development of remanufacturing in Nigeria as Nigeria is grappling with a high unemployment rate, followed by achieving of low carbon footprint, as respondents saw this as a way to transit to a green economy, reduction of greenhouse emission, achieving a zero-landfill reduction. Findings from the questionnaire indicated that creation of job opportunities, achieving of low carbon footprint, reduction of greenhouse gas emission and achieving a zero-landfill reduction.

The drivers of remanufacturing can be classified into six clusters namely Manufacturer's attitude towards achieving green economy, policies to drive remanufacturing, benefits of driving remanufacturing, response to driving remanufacturing, manufacturers drive to remanufacturing and economic benefits of remanufacturing These findings lend support to the possible ways to drive remanufacturing in Nigeria.

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Skilled Electrical Labor Issues in the Mid-Western United States

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Abstract

This research report aims to determine the status of the electrical workforce in the Midwest and identifying ways electrical contractors are overcoming challenges experienced with electrical skilled labor. The objectives of the report include evaluating contractors' perspective on the electrical skilled workforce in the Midwest region, complete a literature review on this topic which includes identifying the current status, causes of the labor shortage in the industry, and potential solutions to the skilled labor shortage in the United States, and determine the methods which contractors are utilizing to become less dependent on the quality/quantity of skilled labor available. The strategy utilized to complete these objectives include conducting a literature review to determine the current state of knowledge on this topic, holding pilot interviews to obtain both qualitative and quantitative data on the status of the skilled electrical workforce, and generating a questionnaire to be provided to a larger population to enhance the level of confidence in the previous findings. The literate review revealed a disconnect between the root cause of the skilled labor shortage and the steps the industry is taking to alleviate it. The construction industry must overcome challenges imposed by industry image and a push for all young adults to attend college. Attracting a younger and more diverse workforce is a primary solution to overcoming a skilled labor shortage. The pilot interviews on the status of the electrical workforce uncovered six main themes affecting the current workforce which includes demand, quality, age, materials, technology, and alternative labor. The questionnaire, developed from these six main themes, verified the need for additional research on this topic as many of the responses received were split 50-50 on these themes. Contractors are concerned about the number of skilled workers due to retire and it's not since they will need to be replaced, but rather the amount of skill and experience which is being lost. Younger skilled labor is perceived to be incompetent in working hard and completing quality work.

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Keywords: Electrical, Skilled Labor, Labor Shotage, Labor Demand;

1. Introduction

Exactly how severe is the skilled labor shortage in the United States. In a survey conducted by the AGC of America, it is the biggest concern of all construction companies and has been growing over the past few years [1]. How did the United States end up with such a shortfall of skilled labor? One of the primary causes of the labor shortage is an issue that plagues the construction industry itself and that is inconsistencies. The construction industry is very volatile and experiences extreme variations in the need for skilled labor which naturally leads to shortages when the economy and industry are doing well. During the last recession, the construction industry lost millions of skilled workers and is finally seeing the employment numbers reach their highest mark since 2008 [2]. Based on data obtained in April, the construction industry currently employs nearly 4.2 million workers, and this does not include workers who build single-

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family homes. This isn't too far off from the number of workers the construction industry employed when it peaked at 4.4 million in November of 2008 [2].

While we are nearing the highest workforce ever employed by the construction industry, forecasts are showing it still isn't enough. The Associated Builders and Contractors estimates at least 500,000 more construction workers are needed to fill the gap. This number would increase by an additional 600,000 if the federal government released more than $1 trillion in infrastructure repair and replacement. To cope with the shortage, many contractors are forming joint ventures and adding staff whose sole responsibility is to recruit new workers from high schools, military bases, and trade schools. The shortage has also created a backlog of work for companies such as Wilmer Electric Services who currently have 18 months' worth of work on the books [2].

Every construction company must have enough supply of quality skilled labor to be successful. The diminished pool of skilled labor means contractors must take what they can get and have little options for picking the best individuals for the job. The lack of quality labor requires the contractor to hold firmly onto the ones they have by offering additional pay or incentives to remain with the company. The overall success of the construction industry lies with their ability to recruit and retain skilled individuals in various construction crafts. Determining the root cause and bringing awareness of the growing labor shortage is the beginning of the rectification process.

2. Literature Review

This section will cover a critical analysis of previously publicized data and information related to the research topic. The literature review is broken into three sections which are relevant to the research aim. The three topics researched include the current state of skilled labor shortage in construction, causes of the skilled labor shortage, and proposed solutions to the skilled labor shortage. Each section will include references from various sources citing similar statistics and rationale for topics related to the labor shortage.

2.1. Current State of Skilled Labor Shortage

To determine a plausible solution to the skilled labor shortage we first must investigate the current status of the issue at hand. The construction labor shortage is well known and has been verified by surveys conducted by the AGC and statistics obtained from the Department of labor. There have also been numerous reports covering this topic with some dating back to the 1980's. The literature review of this topic has quickly show that this is not a new issue and it has plagued the construction industry for many years. The 2017 Outlook Survey completed by the AGC provides great insight in how the construction industry views the current labor shortage. From this survey, 66% of respondents have had difficulty filling skilled labor positions and 75% of the respondents believe it will only get worse [2]. This does not bode well for an industry which is anticipating continual growth.

Like all other construction crafts, the electrician craft has not been immune to the labor shortage. Statistics are showing the situation is possibly getting worse. From the US Department of labor, there were 628,800 electricians employed in 2014 and in 2016 there were 607,120 [3]. The loss of more than 20,000 workers over the past two years laminates the issue of finding these skilled workers as shown in the surveys from the AGC. To make matters worse, the Department of Labor is predicting a 14% increase in employment of electricians between 2014 and 2024. That would place the demand at 714,700 meaning the construction industry must work to add over 100,000 electrician positions in the next eight years. This will be a daunting task as the average age of construction workers is currently sitting at 43 years [4].

Progress has been made in the apprentice program as more than 206,000 individuals entered in FY 16. Of the 505,371 active apprentices, the construction industry employs the most at 144,583. The electrician craft currently has 41,489 active electricians which is just over 4,000 more than the craft had in FY 15 [5]. An increase in apprentices is a good sign, but more growth will be needed to keep up with the current demand.

2.2. Causes of Skilled Labor Shortage

There are many causes that have led to the current skilled labor shortage being experienced by the construction industry. Cataldo [6], states the reasons for the construction labor shortage includes an aging workforce, lack of diversity within the industry, and the industry is simply not attractive to a younger generation. These are just a few reasons which have been discovered during the literature review and each potential cause will be separately identified and analysed. Statistics show the average age of the construction worker is slowly increasing. In 2013, the average age was 42 and in 2015 the average age was listed as 43. While this may seem like a minor increase, the data behind it shows a much more dramatic consequence of having an aging workforce. In Florida, 29% of the construction workers are between 45-54 while another 21% are 55 years are older [7]. With an average of 21% of workers due to retire in the next 7 and an anticipated employment growth of 10% for the construction industry, the problem at hand really begins to magnify [4]. When comparing to other industries, the construction industry has a significantly higher percentage of workers over the age of 45. The actual percentage is 53 while other industries are at 44 percent [6].

Another potential cause for the labor shortage is the image the construction industry has with a younger generation. The NAHB launched a poll and received just over 2,000 responses from individuals between 18 and 25. Of these respondents, only 3% wanted to enter the construction industry as an occupation. The top three desired fields include medical, business, and IT. The top four reasons respondents gave include, wanting a less physically demanding job, construction work is difficult, want an office job, and want to open my own business [9]. A report covering the demographics of the labor shortage lists "an inability to attract new talent" as a long-term reason for the shortage [8]. One which will have a profound affect in the future as the demand for construction labor continues to grow. The push for the younger generation to attend college and not trade schools has weekend the industry's ability to attract young talented workers to its workforce. Sullivan et al [7], report that 65% of high school students in the state of Florida plan on attending college after completing high school. This leaves only a small percentage who may want to join the construction industry and many of which may lack the skills required to be successful. Lack of exposure is a primary reason why many students are no longer looking to the construction industry as a career. Students where once exposed to the industry through shop classes which have mostly been removed high school programs and advisors are not promoting the industry as a potential career option [7]. With the industry struggling to appeal to the younger generation the shortage will only continue to grow as the potential skilled workforce takes positions in other industry's which are more appealing.

A secondary issue with the construction industry's image is its instability. Prior to the great recession, there were 691,900 construction jobs in 2006 and in 2016, even with the economy improving, there were only 457,300 construction jobs which represents a 34% percent decrease [7]. The significant drop off in the construction labor force and its gradual ascension during this time is shown in Figure 1. During this recession, several workers were dislocated from the industry and never returned or plan on returning as they have found positions in other industries [6].

One of the keys to having a successful industry is diversification and the construction industry simply does not have it. A few reports have focused on the demographics side of the shortage and while the results are not necessarily surprising, they do show a significant lack of diversification within the industry. The workforce is primarily made up of white males with the white race representing 66% of labor force in 2010. The other major races include Latinos at 15%, African American at 12% and Asians at 5%. It is anticipated by 2050, the percentages for Whites and Latinos will make up 45% and 30% of the labor workforce respectively. The projection shows no change for African Americans and only a slight increase to 8% for Asians [6]. Immigrant workers also make up a good portion of the construction industry's labor. Across the United States, immigrant workers make up approximately 23% of all construction labor. This is a considerable amount of the labor force which can be drastically affected by ever changing immigration laws. Based on data obtained from NAHB Economics, only 14.1% of all electricians are immigrant workers. Further analysis shows that lack of education is a primary reason for immigrant workers not joining the electrician craft [7].

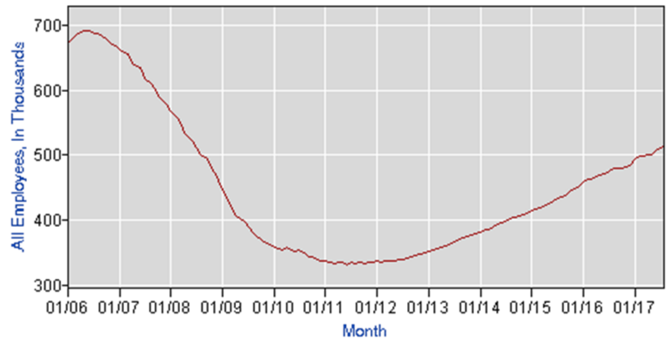

Fig. 1: Construction Industry Labor [3]

Another factor affecting the diversification of the construction industry is the minute percentage which is made up of women. Of all the construction labor force, women only made up 9.1% in 2016 according to the Bureau of Labor Statistics. Sullivan et al [7], note there are three main causes to the lack of participation from women which include knowledge of the necessary skill, a perception of the industry which is unrealistic, and the challenge of performing work which is dominated by males. This is yet another representation of the need for the construction industry to pursue workers outside its typical demographics to fulfil the current demand for skilled labor.

2.3. Proposed Solutions to the Skilled Labor Shortage

To fill the labor gap, the industry should be focused on two areas. The first area which the industry should focus is in attracting new individuals to the workforce and the second would be to work to retain the individuals that already make up the workforce. The following sections will identify the methods currently employed by the industry and what factors attracted and retain the current workforce.

A few of the possible solutions to help bridge the gap include reforming government policies for the use of funds tied to training and education. In a report entitled "An Agenda to Rebuild Our Infrastructure & Our Craft Workforce", the AGC of America listed the following ways to rebuild the construction workforce. The first item the AGC referred to is the Carl D. Perkins Career & Technical Education Act, of which they call for more flexibility for the states to choose where the funds should be best utilized given the labor needs at the time. They also call for changes to the Pell Grant which would allow it to be used by individuals attending career or technical programs. The report suggest that students should be able to participate in technical programs while still in high school and receive credit towards their diploma and be able to enter the workforce trained and ready upon graduation. Other items listed in the report include allowing veterans to get the same assistance for apprentice programs as they would for educational programs and reforming immigration laws to allow for undocumented immigrants who have been working in the United States for years to be converted to legal status. The AGC developed this report and sent it to the new administration in January of 2017 [10]. While many of these changes will help add more individuals to the workforce, it doesn't appear to focus on the all the major causes for this labor shortage. One item which was left out of the report was diversification. It appears the report is focused on doing more of the same and appealing to the groups which currently make up a majority of the workforce instead of developing new methods to reach out to groups who are underrepresented in the workforce.

Training is key to any industry and most of the policy recommendations listed above revolve around making it easier for individuals to receive training prior to entering the craft. In a report developed by Bigelow et al [11], training was found to be a reason which current craft workers chose the construction field as a career and why they have continued to work in the construction industry. The availability of training received the most positive response out of all factors which attracted them to workforce in the first place, even outscoring salary. The results also showed that 78% of electricians stated that provided training is a factor in them staying with the industry [11].

When it comes to attracting and retaining a workforce, there are many factors which apply and can vary greatly between crafts. Of the electrician respondents, 89% stated that an increase in wage would be a positive retention factor and

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salary was one of the primary reasons for selecting the craft to begin with [11]. One of the more surprising statistics from the survey conducted by Bigelow et al [11] was the listing of the industry's image as a positive factor in what attracted them to the industry. This is contrary to most reports which list the industry's image as one of the causes for the labor shortage.

The literature review has provided some key statistics and reports which help to understand the current state of the labor shortage, what are the potential causes, and what the industry believes will help to bridge the gap. The main take away from the literature review is there is a disconnect between the root causes of the labor shortage and the steps the industry is taking to eliminate it. The construction industry must be thorough in developing new methods in attracting a younger and more diverse workforce as their inability to close the gap in the past continues to plague the industry today and will continue to affect the industry in the future.

3. Methodology

A mixed-method research strategy was adopted in the conduct of this research. The research methodology employed for this research report consists of first conducting a series of pilot interviews and analysing the information obtained to generate survey questions. The aim for this research is to provide verification of the electrical worker labor shortage in the Midwest region and share the methods electrical companies and organizations are using to attract individuals to their trade. It was surmised that qualitative data from semi-structured interviews would provide a broad understanding of sentiments from industry professionals. The conclusions from the interview data will provide the basis for an industry wide survey to confirm / refine the findings.

4. Results

As stated in the methodology chapter, a series of pilot interviews were conducted to aid in developing a better survey. The interview was built from information about the skilled labor shortage from the literature review and was geared towards electrical union contractors. Content analysis of the transcribed interview data resulted in six major themes.

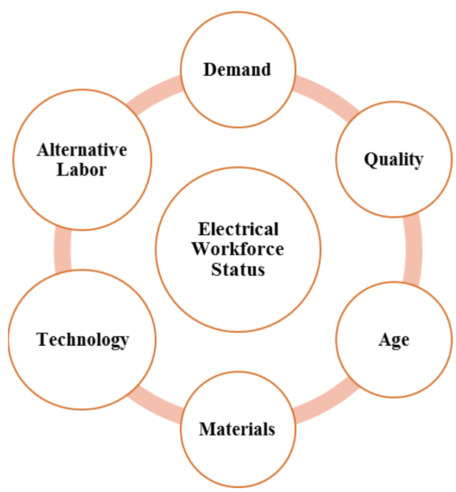

Fig. 2. Themes from Content Analysis of Pilot Interviews

- Demand

The first theme arose from the responses to several questions asked during the interview. The individuals whose primary work is in the metro east, Illinois side of Mississippi river, stated there is a declining market, but acknowledged that it is higher in others. The response obtained from a Missouri electrical contractor stated the demand is "*rapidly increasing*". These two varying opinions of the electrical workforce demand are vastly different even though their jurisdictions are only separated by state lines. The cause of this difference was stated to be "*Illinois politics and just the current state of the Illinois economy*" by one interviewee while the other pointed out that significant amount of work in the metro east comes from industry. This is also why the demand for electrical workers quickly changes. One interviewee referred to the industry as "*volatile*" and of a "*cyclical*" nature. This relates back to information discovered during the literature as a component which dissuades individuals from joining the industry in the first place.

- Quality

Quality was another theme which surfaced from the content analysis. Here, the interviewees revealed that apprentices need to be more skilled due to changes in the industry, but on average they cared less about quality. The lesser quality results from trying to do the work fast and get it done instead of ensuring the work is completed correctly. This presents a serious issue for the industry and contractors alike as poor-quality leads to necessary re-work which in turn affects the profitability of the contractor. The older generation took great pride in their work and there is hope the newer generation will "*grow into the skill*" thus higher quality will follow.

- Age

When referring to apprentices, the opinion varies between the interviews on whether they are getting older or younger. One interviewee stated that "*20 years ago, it seemed like we always interviewed and brought in guys that are in their early twenties. I see apprentices now, seem to be even older*". While their opinions were inconsistent with the age of apprentices, they all stated that the average age of their electrical workforce was in their 40's. One interviewee even broke their labor force down into the following statistics, "*we have 27% baby boomers, 32% gen X, 39% millennial generation and then now we're even coming into gen Z at about 2%*". These statistics and average ages are in line with the national statistics for the electrical workforce as provided in the literature review.

- Materials and Technology

The next two themes discovered during the content analysis were materials and technology. These are grouped together as they go hand and hand in helping to create a more efficient workforce. Contractors can order materials from suppliers in a fashion called kitting in which every component for a room or job are packaged in one box which reduces the time a skilled individual spend rounding up the necessary materials for a specific project. Suppliers have improved the coatings on conduit to make it easier to pull without the need of adding soap. Technology has also led to new work for the electrical industry. As one interviewee stated, "*there are smart tools now that the count crimps and have the right pressure for different things that are logging, spitting out logs automatically for the number of times that something was torqued and even locational things*". All of this has helped the electrical industry to become more efficient and overcome potential shortfalls of a skilled labor force.

- Alternative Labor

The last theme developed from the content analysis was the use of alternative labor. Each interviewee discussed using less skilled labor to perform certain duties associated with the electrical craft. Improvements in technology and materials has helped spurred this as some tasks have been simplified such as one interviewee stated, "*It's as simple as even wire, you think how can you improve wire? It's a simple product now they make it in colour. They're making it red, blue, so you don't have to think about what phase each one is when you pull it in*". This allows contractors to use a less skilled workforce which in turn frees up some of the skilled workforce to complete more complicated task. As with any company, electrical contractors are always looking for efficiencies and developing a competitive advantage over other contractors.

4.1. Survey Design

The survey was designed with the aid of information obtained about the skilled labor workforce form the pilot interviews conducted previously. A total of 21 questions were posed to participants along with an ability to post comments for each question. Some open-ended questions also posed to participants, thus allowing them to propose ideas beyond the questions asked.

4.2. Survey Results

To ensure the responses were being generated by personnel within the company who have direct ties to the electrical workforce, the first question sought demographical information about participant's role within the company. The results from this question were positive as 25% of the respondents were the owners of their respective companies, 25% were the company president, 25% were either vice president or company CEO, 17% were project managers, and 8% were corporate secretaries. Participants were asked about company and as seen in Figure 3, 67% of the responses were received from companies with 50 or less employees. While the remaining 33% employed 51 or more. Continuing with developing an understanding of the company, respondents were asked about the type of electrical work the contractor typically worked on. For this question 92% of respondents worked on commercial contracts. 41% of the respondents selected other and specified project types such as cell towers, electrical signs, healthcare, telecommunication, and renewable energy. The results from the survey are found below in Figure 4.

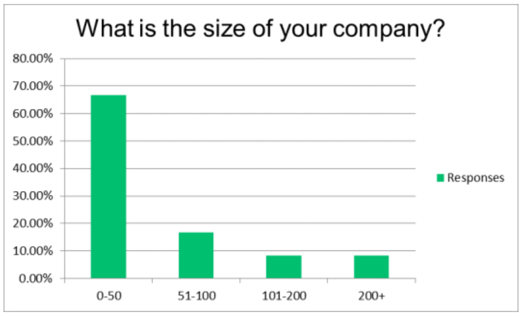

Figure 3: Company Size

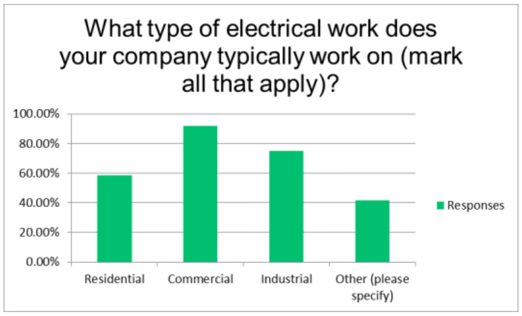

Figure 4: Electrical Work

To make sure the survey was being responded to by electrical companies in the Midwest, the next question aimed to identify which regions of the United States the company does work. This resulted in a 100% success rate of companies working in the Midwest with a few of the companies also performing work in other regions as seen in Figure 5.

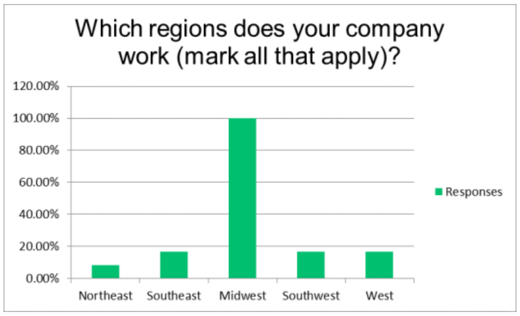

Figure 5: Regions

Participants were asked about the status of the electrical workforce is in the Midwest. Almost 60% of the respondents feel the current demand for their services is normal while 33% feel the current demand is lower than normal as seen in Figure 6. Additional comments received from this question noted the cyclical nature of the industry and that work was busier than normal over the last year, but the contractor is currently experiencing a slight slowdown. They also made mention that the type of work which they are involved in is more diverse than it was in the past. The next question requested that the respondents consider the future and forecast what they believe will be the change in demand over the next year. Here, 42% of respondents believed the demand will increase as seen in Figure 7. Another 25% responded the demand will decrease and the remaining 33% believe it will remain the same.

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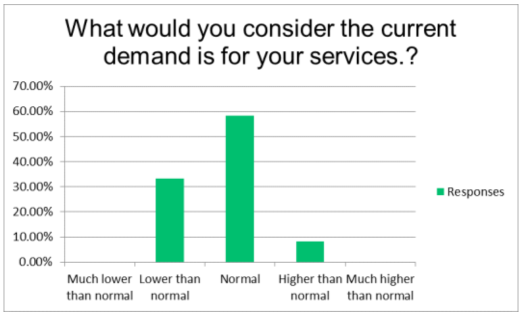

Figure 6: Demand

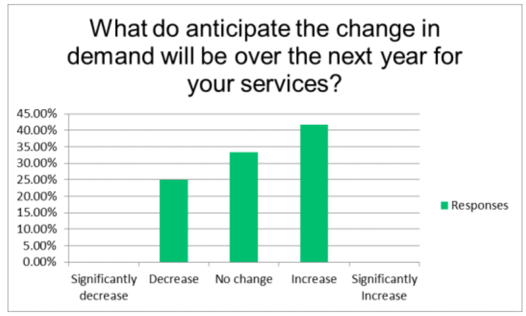

Figure 7: Change in Demand

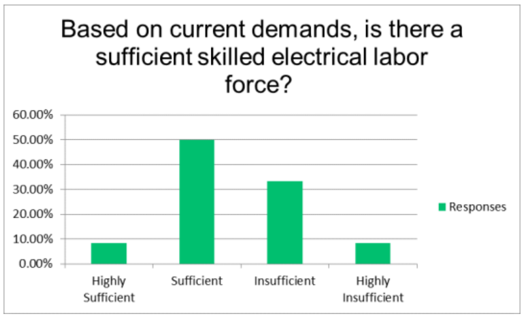

Figure 8: Sufficient Labor Force

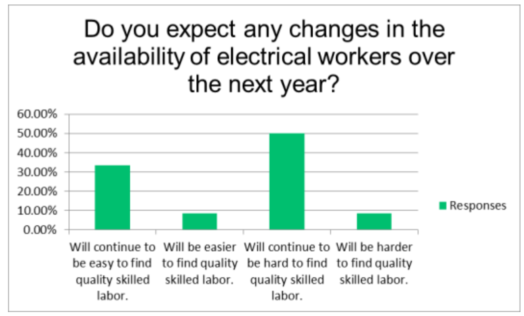

Figure 9: Change in Availability

Participants were asked if contractors consider the skilled electrical workforce enough regarding the current demand. The results revealed 58% of respondents feel there is enough or highly sufficient workforce while the other 42% feel it is lacking as seen in Figure 8. One comment received states, "*The downturn from 2008-2012 created a gap. Less apprentices entered the trade. Many tradespeople took maintenance positions.*". This belief is consistent with what was discovered during the literature review. Skilled workers lost their jobs during the recession and didn't return when the jobs came back. The next question received a similar distribution of responses when asked if they believed there would be any changes in the availability of electrical workers in the next year. 58% of respondents believe it will continue to be hard or even become harder to find these skilled workers while the other 42% believe it will be easier, as shown in Figure 9. Contractors provided additional comments to this question which relate to similar themes discovered during the interview portion of the research. While another gives credit to technology for reducing the amount of manpower required to complete projects.

The next question aimed to see if contractors were satisfied with the skill set of electrical apprentices. While 42% of the respondents stated they are neutral on this subject, 33% were dissatisfied and the remaining 25% were very satisfied as shown in Figure 10. Participants were asked contractors to rate the overall quality of new electrical skilled labor in their region. The respondents replied with 75% average or above average, while the other 25% felt the quality was below average, as shown in Figure 11.

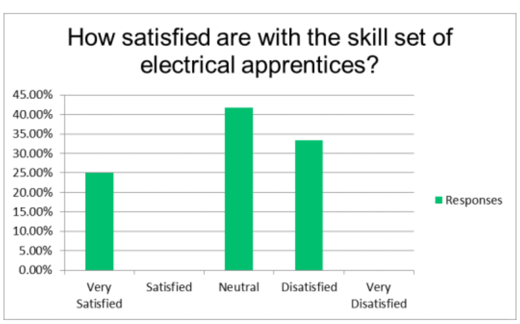

Figure 10: Electrical Apprentice Satisfaction

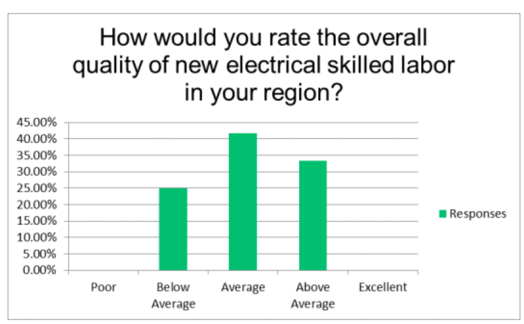

Figure 11: Rating of New Skilled Labor

The next question asked contractors to provide ways which technology has improved the electrical industry. While most of the respondents noted an improvement in materials, equipment, plans and training, nearly 17% stated that they have seen no noticeable improvement as seen in Figure 12. One respondent offered the following examples of how technology has helped to improve the industry, "*Prefabrication and modularization allows us to build earlier and in better environments. Layout is twice as fast with robotics, wire pulls require 2 men not 6, iPads streamline info and collaboration*". This response offers a few ways in which efficiencies have been obtained by improvements to products and methods made possible by advances in technology. Participants were asked to weigh in on if there have been any changes in workforce efficiencies over the past 5 years. Based on the previous answers, it seems like it would be a safe assumption to say yes, however only 25% of respondents feel the workforce efficiency has improved. Most of the respondents felt neutral on this topic while 17% feel efficiencies have declined. The results from the question can be found in Figure 13.

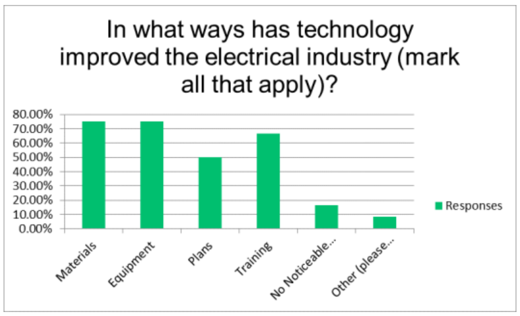

Figure 12: Technology Improvement

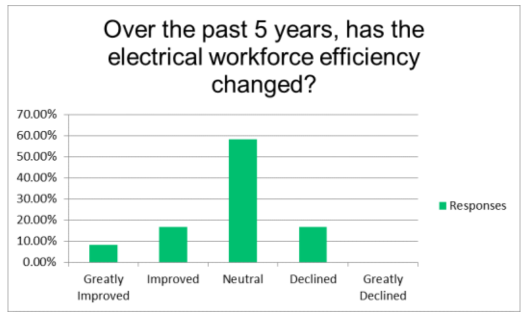

Figure 13: Workforce Efficiency

Respondents were asked to provide methods that they have used to increase efficiency on electrical projects. Of the results received, 25% stated they used prefabrication while 17% noted better tools, communication, and modelling software (BIM) to increase efficiency.

Due to all the attention given to the number of individuals due to retire in other skilled trades, participants were asked about the topic. Of the responses received, 67% stated they are slightly concerned to highly concerned about this topic while 33% have no concerns as seen in 14. One contractor commented, "*There are skill sets that will be lost as the next generation has different experience i.e. conduit bending - younger generation has only received prefabricated bent conduit, limited hands on bending*". While the results show many contractors are concerned about the number of electricians due to retire, the responses were split evenly when asked if they are concerned the industry will not be able to recruit enough workers to replace those who do retire as seen in Figure15. One respondent noted, "*Industry still structured for 100-man projects that now only require 60*". This brings some light as to why some contractors are not concerned with the heavy loss of retired workers.

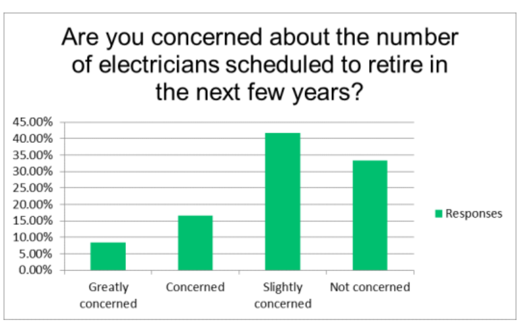

Figure 14: Retirement Concern

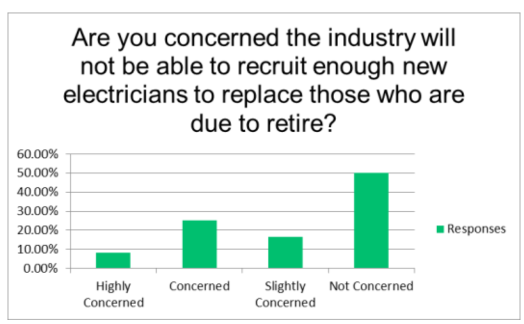

Figure 15: Replacement Concern

Participants were asked if they have found it difficult to retain electrical workers. Here, 75% of the respondents are neutral on the topic as many of them feel it is the union's responsibility to provide a workforce. The union also limits what contractors can and cannot do to incentivize and attract union electricians to their company, as shown in Figure 16. The following question sought to discover what strategies contractors have used to retain workers. The results revealed 36% of the respondents used higher pay or bonuses to retain individuals while 45% provided a response which was not an option as seen in Figure 17. These responses included more work, improved culture, and since they are a union shop, the workers already have the best pay and benefits in the industry.

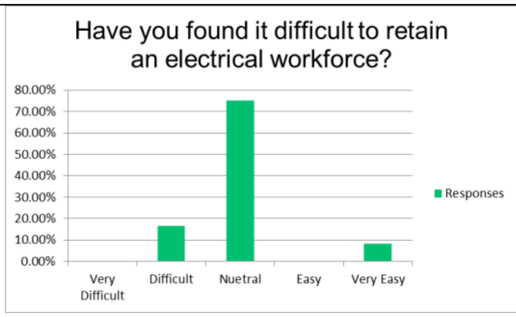

Figure 16: Difficult to Retain

Figure 17: Strategies to Retain

An open-ended question asked respondents to discuss what challenges they foresee retaining employees in the future. Of the responses received, 20% feel a lack of work or slowdowns in the industry and keeping the workforce happy and content will be their biggest challenge. Others noted that finding individuals with a good work ethic will prove to be difficult.

Participants were asked if they have used a less skilled worker to complete certain task on electrical projects and if they have or have not had issues. Of the responses received, 42% have not utilized while 33% have with success and the other 25% have used with issues as seen in Figure 18. Additional comments received on this topic noted the additional planning and oversight which is needed to employ less skilled individuals as well as a loss in efficiency. The penultimate questions was asked to see if union contractors participate in recruiting activities or if they are completely reliant on the union to attract skilled workers. The results shown in Figure 19 show a near 50-50 split between those who occasionally or actively participate versus those who rarely or never participate.

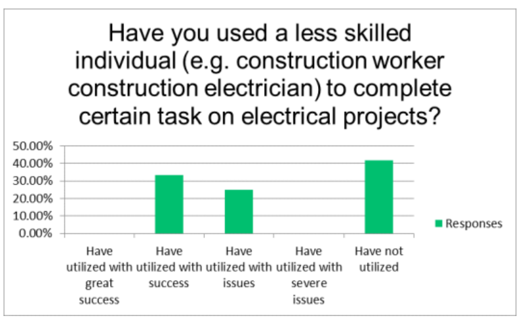

Figure 18: Less Skilled Labor Usage

Figure 19: Recruitment

The final question was asked contractors to provide what they feel is the best way to recruit and develop the next generation of electrical workers. 27% of the responses received stated training as the best way to develop the next generation. One respondent noted, "*The next generation needs to become mature and understand they must work to be retained by the company. The next generation does not understand "hard work" and assumes the position will come easy and that education, on their part, is a must*". The words which the respondent has quoted, "*hard work*" is key to attracting individuals to the construction industry. It was discovered during the literature review that many people of the younger generation are afraid of hard work and working with their hands. This is a generational issue where older generations functioned off a "*live to work*" mentality and the newer generations follow a "*work to live*" mentality. Also affecting the younger generation is the plethora of opportunities which weren't available to older generations thus affording them the ability to be less concerned about losing a job as other jobs may become available. Another respondent provided, "*Definitive career path to journeyman wireman - current entry programs have ambiguous future. Work hard to resurrect the pride of being a trained craftsman. STEM programs in high schools, much of an electrician's responsibility is based upon math, science, and cutting-edge technology. Change recruiting message - realization that a 4-year degree isn't for everyone, in lieu of borrowing $40k a year for four years to get a $40k a year job (if you're lucky), you can make $40k a year for four years and become a tradesman/woman making $75k a year with great benefits*". This is a great selling point for the union and electrical industry and getting the word out would be an excellent way to attract a younger generation.

5. Conclusions and Recommendations

The research conducted captured the current state of the Union electrical workforce which is just a snapshot in time. While the research did not discover any new or different trends that sets the skilled electrical workforce apart from other skilled construction labor, it was discovered that the electrical skilled labor shortage seems to be less of an issue in the Midwest when compared to the construction industry in general. Unions have been able to provide enough workforce to meet the needs of contractors over the last few years and many journeyman electricians and apprentices are currently unemployed in the region. The cyclical nature of the construction industry is truly feast or famine and can change very quickly. A benefit of being a union contractor allows them to forego the worrying of retaining and attracting new workers to the electrical workforce as this is the Unions job. However, nearly 50% of respondents do have a concern about the current labor situation and what will happen soon when approximately 20% of the current workforce retires.

The research revealed a few ways in which contractors are making themselves less dependent on this skilled labor. The material suppliers have realized this and are making electrical components more installer friendly and can even kit all the necessary components for wiring a room in one box, so the skilled electrician does not need to waste time tracking down the materials. Another component in increasing effectiveness and efficiency are developments in new technology which will continue to play a big role in making the industry less dependent on skilled labor. One common response from the interviews and surveys resonates the idea that, at least in the electrical industry, the efficiencies gained will help to overcome the challenges faced in recruiting new workers and retaining those already in the industry.

Researching and comparing multiple regions at the same time could provide key information on where the labor shortages and surpluses are most prominent. The labor shortage appears to be a regionalized issue as not all areas in the country are experiencing the same construction boom. This can be attributed to multiple factors which would lend itself to another study. Another recommendation would be to conduct the same surveys at different times of the year and with different construction skilled labor workforces to determine if there is any correlation between the time of year and workforce demand. This would also be highly affected by region as in northern states, many contractors are unable to work year-round due to temperature and weather. Based on responses received during the data collection process, it would be interesting to complete additional research to determine if the efficiencies gained through technology, materials, and tools are enough to overcome the skilled labor shortage. This appears to be the industries current mechanism for coping with potential shortages now and in the future. The final recommendation revolves around data gathering. The primary source of data collection for the survey's included gathering emails of perspective contractor's and send a link to an established survey. This was thought to be the easiest and most effective way to reach out to a larger population over a short period of time. In the end, many contractors disregarded the emails and only a small number of responses were received. Recommendations for future research on these topics in which a large population is desired would be to team with a contractor organization or union leaders to help encourage a better response rate.

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Supply Chain Management In The Ghanaian Building Construction Industry: A Lean Construction Perspective

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Abstract

Supply Chain Management (SCM), for the past two decades, has been identified by manufacturing industries as a new way of doing business. Construction, just like the manufacturing and other services industries, is experiencing emerging trends that are aimed at giving ultimate satisfaction to the end user. Lean Construction is a way to design production systems in order to minimize waste of materials, time, and efforts that generate maximum possible amount of value. This research looked into how supply chain management can benefit the Ghanaian building construction industry through the application of lean concept. The purpose of this study is to assess the level of collaboration and coordination in planning of activities among construction industry players, and investigate into the sources of waste in construction. The study is considered as qualitative case study. Data is collected through questionnaires, in depth interviews and direct observation of on-going projects on KNUST campus. One sample t test is used to analyze the data. The findings pointed out that the level of coordination and collaboration in planning among industry players were very appreciable though there still exist room for improvement.

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Keywords: construction; lean; supply chain management; value; waste

1. Introduction

Supply Chain Management (SCM), for the past two decades, has been identified by manufacturing industries as a new way of doing business [1]. The ever changing manufacturing environment such as development of Information Technology (Internet), globalization and sophisticated customers who demand increasing product variety, lower cost, better quality and faster response has accounted for the implementation of this new approach. SCM as explained by Christopher [2] is concerned with the management of upstream and downstream relationships with suppliers and customers in order to deliver superior customer value at less cost to the supply chain as a whole. The primary focus of SCM, Christopher [2] continues, include seeking to achieve a linkage and coordination between the processes of other entities, reducing buffer of inventory that exist between organizations in a chain through information sharing, as well as ensuring cooperation and trust among all involved in the supply chain.

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Ayers [3], concludes that SCM has untapped potential for maintaining a competitive position or moving a company from an unfavourable to a more advantageous position. SCM therefore presents an especially important domain which is crucial to achieving a consistently successful performance.

Construction Supply Chain Management is an emerging area of practice which is inspired by but differs substantially from manufacturing SCM, which places emphasis on modeling volume production. Construction SCM on the other hand is concerned with the coordination of discrete quantities of materials delivered to specific construction projects [1]. The Construction industry generally is known to be a very vibrant and primary contributor to the economy of every nation in terms of employment generation and gross domestic product. This is evident in the employment opportunities it offers skilled and unskilled labour, from engineers and consultants to artisans and labourers [4]

Construction, just like the manufacturing and other services industries, is experiencing emerging trends that are aimed at giving ultimate satisfaction to the end user. As in the manufacturing context, construction companies are facing increasing competition and customers are requiring lower costs, higher quality, shorter execution durations and more reliable schedules [1]. The industry is characterized by the adoption of traditional methods of procurement and planning project executions with very little room for logistics and supply chain management. This has led to a situation where most projects are completed well over the contract duration whiles incurring avoidable costs, hence a reduction in turnover [1]. Inadequate management of logistics also has an adverse effect on quality, causes delays to projects, and adds to the health and safety risks on site. Additionally, construction supply chain is still full of waste and problems caused by myopic control [5].

One strategy for coordinating within and between firms with a focus on achieving efficiency, eliminating waste or overburden and creating value in products is the concept of lean management [6]. Ballard and Howell [7] further argue that construction project management is activity or contract centered, with transactional contracts or assignments defining and balancing the objectives of various participants thus making it ripe for the occurrence of costs and errors. Thus while project management views a project as the combination of activities, lean thinking views the entire project in the production system terms, that is, as if the project were one large operation.

Lean concept, which was coined in a book co – authoured by Jim Womack, Daniel Jones and Daniel Roos called *"The Machine That Changed The World"*, evolved from the Toyota Production System in Japan and is a philosophy which considers the expenditure of resources for any goal other than the creation of value for the end customer to be wasteful, and thus a target for elimination [8].Holweg, [8] further defines "value" as any action or process that a customer would not be willing to pay for. This concept, which was originally designed to suit the manufacturing industry, has not allowed the construction industry to benefit fully as a result of the one of a kind type of production as against the mass production in manufacturing. Lean therefore employs continuous improvement efforts which focuses on eliminating waste or non – value adding steps along the supply chain.

Koskela et al, [9], defines Lean Construction as a way to design production systems in order to minimize waste of materials, time, and effort in order to generate the maximum possible amount of value. They further argue that, lean construction concerns itself with the holistic pursuit of concurrent and continuous improvements in all dimensions of the built and natural environment. This approach tries to manage and improve construction processes with minimum cost and maximum value by considering customer needs. The goals of lean construction, according to Ballard and Howell [7], redefine performance against three dimensions of perfection; (i) a uniquely custom product, (ii) delivered instantly with (iii) nothing in stores. This, they assert, is an ideal that maximizes value and minimizes waste. The formation of the International Group of Lean Construction that holds annual conferences has propagated the concept of Lean construction which according to Formoso and Moura, [10], the application of it has been widely successful in countries such as USA, Brazil, Chile, Ecuador, England, Finland, Denmark and other countries.

Whereas the application of supply chain management techniques has been known to save millions of dollars whiles improving on customer service in the manufacturing environment [11], its importance in the construction environment cannot be underestimated. Supply chain management promises an engineering basis to design, plan, and manage construction projects in a collaborative manner as against the current construction methods which takes a hierarchical, decomposition approach which seeks at best to optimize individual activities [1]. This ultimately tends to support the fragmentation that plagues the construction industry. On the other hand, according to Bertelsen, [12], a poorly designed supply chain regularly increases project costs by ten percent hence the need to employ best practices if the full benefits of supply chain management in construction are to be achieved.

Research on improving the quality, performance and delivery in the construction industry in Ghana through the adoption of lean concept largely centres assessing perceptions of lean construction philosophy, identifying level of knowledge, barriers to the adoption of lean construction and possible means to overcome these barriers as well as level of contribution of waste minimizing measures and the level of their practice of such measures [13], [14], [15], without identifying the sources of waste. The main motivation of this research is to provide an approach to improving the performance of the construction industry in Ghana through the concept of lean thinking. The objective of the study is to assess the level of collaboration and coordination in planning among construction industry players and also investigate into the sources and causes of waste in the construction industry. A theoretical framework for SCM and lean construction is developed in Section 2 of the study, whiles Section 3 deals with research methodology. Research results are analysed and discussed in Section 4. Finally, Section 5 concludes the study.

2. Theoretical Framework

2.1 Supply Chain Management

Stock And Boyer [6], while stating that there exist much confusion among researchers on the definition of SCM, do acknowledge commonalities like coordination, integration and cooperation among chain members. SCM, according to Christopher [3] is a network of connected and interdependent organisations mutually and co-operatively working together to control, manage and improve the flow of materials and information from suppliers to users. The primary concerns of SCM, Christopher [3] continues include (i) achieving linkages and coordination between processes, (ii) removing or eliminating buffers of inventory that exist between organisations in a chain through information sharing, (iii) ensuring co-operation and trust, (iv) managing relationships in order to achieve a more profitable outcome for all parties and (v) achieving competitive advantage.

The need for coordination between suppliers and distributors, in order to survive competition in the international market if further reinforced by Janvier – James [21]. Mentzer et al. [22] however simplify SCM activities to include integrated behavior, mutually sharing information, mutually sharing risks and rewards, cooperation, the same goal and the same focus on serving customers, integration of processes and partners to build and maintain long – term relationship.

2.2 Lean Thinking

Lean thinking was pioneered by the Toyota Production System (TPS) with a focus on waste elimination, continuous flow, and customer demand pull, which is otherwise referred in manufacturing as Just-in-Time production [16]. Lean thinking has three guiding principles according to Fitzsimmons and Fitzsimmons [16] and they are:

1. Satisfy the needs of the customer by performing only those activities that add value in the eyes of the customer.
2. Define the "value stream" by flowcharting the process to identify both value added and non-value added activities.
3. Eliminate waste. Waste in the value stream is any activity that the customer is not willing to pay for.

Ballard and Howell [7] on the other hand states the principles of lean thinking as (i) stopping the line, (ii) pulling product forward, (iii) one-piece flow, (iv) synchronise and align, and (v) transparency.

2.3 Lean Construction: Definition and Principles

Koskela [17] explains that Womack and Jones in their book "The machine that changed the world" did not concisely summarized the principles of lean production. Hence in their newer book (1996), Womack and Jones endeavoured to improve the theoretical side of the discussion of lean production. Consequently, they summarized the principles underpinning lean thinking as:

- Precisely specify value by specific product
  The central message of this principle is to rethink value from the perspective of the customer. The only thing that adds value in any type of process, is the physical or information transformation of the product, service or activity into something the customer wants.
- Identify the value stream for each product
  Value stream is about modeling and designing of the production system, including product development, order fulfillment and the production proper, especially with the goal of weeding out avoidable wasteful activities.
- Make value flow without interruption
  This principle, while addressing generally the reduction of lead times, refers basically to the method of one-piece flow, instead of a flow consisting of batches.
- Let the customer pull value from the producer
  This principle means that the customer is pulling the product from the production system as needed rather than the production system pushing products, often unwanted, onto the customer.
- Pursue perfection
  This is all about continuous minimization of waste and maximization of value, that is, continuous improvement.

2.3 Lean "Wastes"

Waste should be understood as any inefficiency that results in the use of equipment, materials, labour, or capital in larger quantities than those considered as necessary in the production of the activity. Waste therefore includes both the incidence of material losses and the execution of unnecessary work which generates additional cost but do not add value to the product [15]. Formoso et al. [10] also defined waste as any losses produced by activities that generate direct or indirect costs but do not add any value to the product from the point of view of the client. Ohno [18] defines waste into seven categories that are apparent in every manufacturing facility in the world. An eighth was added by Liker [19]:

1. Waste of overproduction
2. Waste of waiting
3. Waste of transport
4. Waste of over processing
5. Waste of inventory
6. Waste of motion
7. Waste of defects
8. Waste of unutilized people

- Waste of overproduction
  This type of waste occurs when production is over what is immediately needed for use. That is, non – value adding use of available capacity leading to producing more and faster than the customer requires. Inventory stockpile, unbalanced material flow, extra resources and complex inventory management are some of characteristics of overproduction.
- Waste of waiting
  This result from any idle time created whiles waiting such as idle time between operations or events. The waiting could be done by employees or customers, either of which is still a waste. Employees waiting for

machines, machines waiting for employees, machines waiting from machines and unplanned equipment breakdown result in waiting related waste.

- Waste of transport
  Any movement of materials or people around a plant that does not add value to the product or service is considered waste of transport**.** That is, movement of materials, finished goods, parts or information more than required resulting in wasted efforts and energy and adding to cost. Paperwork loop-back, large lot processing, multiple storage location and lack of work place organization give rise to transport waste.
- Waste of over-processing
  This waste is about adding more value than the customer would pay for or any effort that adds no value to the product or service. In other words, processing more than required wherein a simple approach would have done. This generally results from lack of clear customer specification, endless refinement and ineffective policies and procedures.
- Waste of motion
  Any movement of people or machines that does not add value to the product or service. Characteristically, excessive bending and reaching, looking for tools, machines or materials too far apart, confusing motion with work and lack of work place organization results in waste of motion.
- Waste of inventory
  Storing parts, pieces, documentation ahead of requirements, that is, any supply in excess of customer requirements necessary to produce just in time is waste of inventory. Queuing, callers on hold, large storage areas, piles of request, use of large inventories and slow response to change result in this kind of waste.
- Waste of defect
  Anything that does not meet customer needs leading to rework, scrap and inspection and repair of materials in inventory. This type of waste result in excessive human resource to rework, scrap, repair or inspect, missed shipment and deliveries and lower profit margins due to rework and scraps.
- Waste of unutilized people
  When employees are not leveraged to their own potential, that is, using people to the best of their unique abilities, there is a waste of intellect. This usually results from lack of employee involvement, poor morale, status quo not challenged and lack of team activities and accountability.

2.4 Lean Tools

Numerous tools have been developed along with lean philosophy including, Kaizen, 5s, the Last Planner system, and the Value stream mapping. 5s is a set of techniques providing a standard approach to housekeeping within Lean. Kaizen also deals with continuous improvement process where everyone is encouraged to come up with small improvement suggestions on a regular basis. Kanban on the other hand which means “signboard” or “billboard” and works on the basis that each process on a production line pulls just the number and type of components the process requires, at just the right time. It is a means to achieve Just-in-time [17].

3. Methodology

The research adopted a case study approach, with tools for data collection being face – to – face unstructured interviews, semi – structured questionnaires and direct observation. The cases studied involved 4 on-going building projects on the campus of KNUST. 10 construction professionals were interviewed, with 80 questionnaires administered. A total of 63 valid questionnaires were returned, representing a response rate of 78%. Respondents were randomly sampled from all construction professionals employed on the building projects that were studied. Questionnaire was primarily in two parts. The first part was on collaboration and coordination in planning activities among industry players. In the second part, respondents were asked to rank, in order of importance on a 5 – point likert scale, 24 identified sources of waste on construction sites. Also, respondents were made to share their knowledge and understanding of waste, the possible consequences of waste, tools for waste identification and benefits to an organization on waste identification and elimination. The summary of building projects studied are in Table 1 below.

Table 1: Characteristics of Case Projects

Project Name	Contract Sum (US$)	Contractor
Construction of 4 – Storey Examination Block	5,500,000.00	Berock Ventures Limited
Construction Of 4 – Storey N – Block for the College of Engineering	6,200,000.00	Berock Ventures Limited
Construction of VIP Ward for KNUST Hospital	2,200,000.00	Stivo Company Limited
Construction of3 – Storey Computer Laboratory And Canteen Block for KNUST JHS	1,500,000.00	Asib Company Limited

Data collected was analysed using descriptive statistics and one – sample t – test at 95% confidence interval. Thus SPSS was used to calculate mean scores and standard deviations. Mean scores of greater than 3.00 were considered significant for the research [20]

4. Results And Discussions

4.1 Coordination And Collaboration

As seen from above, SCM largely thrives on coordination, co-operation and integration among all parties along the supply chain that have the ultimate goal of ensuring consumer satisfaction. Means scores as found in Table 2 below indicate that all other stakeholders have very cordial relationship among themselves. Clients rated the level of coordination and collaboration with other stakeholders highest, recording a mean of 4.67.

Table 2: Level of coordination and collaboration among industry players

	N	Mean	Std. Deviation	Std. Error Mean
Consultants	63	4.48	0.602	0.131
Subcontractors	63	3.90	0.944	0.206
Major Suppliers	63	4.14	0.910	0.199
Clients	63	4.67	0.483	0.105

5.2 Communication And Information Sharing.

Effective collaboration and coordination largely thrives on information sharing. Information sharing can also be as effective as the mode and effectiveness of communication. Respondents generally agreed that there existed a cordial relationship among all parties with respect to communication and information sharing. This is evident in all respondents having mean scores in excess of 3.00. Consultants indicated the greatest level of agreement, followed by Clients, subcontractors and major suppliers in that order, as indicated in Table 3 below. The modes include site meetings, letters, site instructions and phone calls. Electronic means such as emails were seldom used though communication between Sub Contractors and Main Contractors occasionally employed this mode.

Table 3: Communication and information sharing

	N	Mean	Std. Deviation	Std. Error Mean
Consultants	57	4.68	0.478	0.110
Subcontractors	60	4.30	0.571	0.128
Major Suppliers	60	4.25	0.550	0.123
Clients	63	4.43	0.746	0.163

It came to light from the interview with the consultants that these meetings are held on monthly basis and may be reduced to bi-weekly when a particular project is nearing completion. It was also found out that aside monthly site meetings, technical meetings are scheduled to iron out critical and pressing issues that may arise in between monthly site meetings. Interviewees generally believed the regular nature of the meetings help to clearly define roles, address issues, set targets and source for ways of achieving them.

Site meetings and Technical Meetings provide an effective avenue for all parties to deliberate on issues bothering on the smooth execution of projects. It is at these meetings that wide range of issues that will promote the efficient site management and material deliveries are discussed. Other issues include the clarification of discrepancies in working drawings, waste generating activities and any other issues that militate against the smooth execution of projects are looked into and solutions found. Meetings also serve as a conflict resolution platform.

Since meetings bring together all these players under one umbrella at a time, coordination and collaboration is greatly enhanced. One set back that cropped up was that it was not an uncommon practice to find some members not present at these meetings. Members who absent themselves may sometimes delegate their subordinates to stand in for them but most of these subordinates may not be as resourceful and well informed as their superiors. As one interviewee puts it, it is not an uncommon occurrence to find the representative of the main or subcontractor not having information regarding the honouring or otherwise of payment certificates. He further continued that especially in cases where contractors are behind schedule and they are responsible for the delay, they tend to skip site meetings and prefer to be represented by their subordinates. On the part of Consultants, Structural, Services and Maintenance Engineers are not resident at the Office of Physical Development and due to other engagements by these persons, they may not be able to attend site meetings though their inputs may be required at the particular time.

Meetings aside, parties also communicated through the writing of letters and telephone calls. Contractors are encouraged to write letters to confirm oral instructions and channel concerns to Consultants as these letters form part of the contract. It was revealed by interviewees that the main mode of communication among subcontractors, main contractors and major suppliers is through telephone calls. Site Supervisors mostly said they often called Consultants over the phone to seek clarification or invite them to site to sort out urgent issues. They all agreed that the response rate was very appreciative though there still exist room for improvement. One Sub Contractor however stated that, there are times as a result of the bad nature of telecommunication service in the country, they have not been able to link up with people they may wish to contact. Consultants main concern was that request for information and clarification should be done well in advance to ensure that adequate and rich responses are given. This they say will prevent instances where responses are given in a rush which may prove not to be the best advice.

4.3 Coordination In Planning

The results prove that generally the various players took into account the concerns of others when planning their activities. This is because there exist healthy relationship among players. Respondents ranked the relationship that exists among them as very healthy. It was found out from the interview with subcontractors that they also see the relationship between themselves, main contractors, consultants and clients as very healthy. Consultants held the same view. The planning of activities by Main Contractors were influenced to a greater extent by Consultants, Sub Contractors and Major Suppliers and the reverse also holds true. This explains the higher levels of coordination among all parties. It is therefore not surprising to find activities such as defects, unnecessary work, poor storage of materials and poor quality of work are not usual occurrences on site and hence not a source of waste for the purpose of this study. Coordination in planning of activities by all parties ensures that work is done according to specification, doing the right thing at the right time and allocation of the right type and quantity of materials to the right type of activity. Table 3 summarizes the level of agreement to coordination in planning of activities.

Table 4: Coordination In Planning Of Activities

	N	Mean	Std. Deviation	Std. Error Mean
Consultants	63	4.57	0.746	0.163
Sub Contractors	60	3.65	1.137	0.254
Major Suppliers	60	3.30	1.380	0.309
Clients	60	4.20	1.005	0.225

Strong coordination among parties on a project will be step in the right direction towards the successful completion of a project. This is because, individual companies with separate corporate interests have come together to execute a particular project. One Sub Contractor who installs Lift states that he can only move to site after the main contractor has finished with all concrete works related to the lift well. This he states further explains how reliant he is on the main contractor. He however agreed that the main contractor would also have to wait for him to finish with his works before making good any works disturbed. All interviewees agreed that they can hardly achieve the level of success required of them if they do not take into account the concerns and influences of other players. Team work, to them, is the watch word.

The picture is not all rosy as there is the need to still improve on the level of coordination in planning of activities among industry players as pointed out by one interviewee. Slow decision making and instructions by Consultants, shortages of materials and waste of materials proved to be significant sources of waste according to respondents and can directly be attributed to problems in the level of coordination in planning. Proper internal coordination in planning of activities should prevent other sources of waste like inefficient movement of workers and delays in arrival of workers. Externally, Consultants would also better appreciate the positive impact the timely issuance of instructions will have on the project.

4.4 Wastes In Construction.

For the purpose of this study, waste is understood to be any losses produced by activities that generate direct or indirect costs but do not add any value to the product from the point of view of the client. Respondents understood waste to mean one of the following: leftovers of materials on site, unwanted material, excess material not used after a construction activity, materials that are supposed to go into the works but do not find their way into the works, percentage of material which was not used as intended as a result of improper usage and/or supervision and any unwanted materials. In line with the set criteria, items O – X, with means scores of less than 3.00 were considered insignificant.

Table 5: Sources of waste

Item		N	Mean	Std. Deviation	Std. Error Mean
A	Delays in arrival of workers, plant and materials	63	3.7619	0.70034	0.15283
B	Slow decision making and instructions by Consultants	63	3.6190	0.74001	0.16148
C	Waste of materials	63	3.5238	0.74960	0.16358
D	Shortage of materials	63	3.5238	0.87287	0.19048
E	Inefficient movement of workers	63	3.3810	0.80475	0.17561
F	Poorly scheduled delivery of materials to site	63	3.2857	0.84515	0.18443
G	Accidents	63	3.2381	0.62488	0.13636
H	Excess materials in store	63	3.1905	0.92839	0.20259
I	Waiting and idling	63	3.1905	0.92839	0.20259
J	Double handling of materials	63	3.1429	0.91026	0.19863
K	Use of materials over and above specifications	63	3.1429	0.96362	0.21028
L	Deterioration of materials	63	3.0952	0.76842	0.16768
M	Rework	63	3.0476	0.80475	0.17561
N	Unnecessary or not enough information flow	63	3.000	0.89443	0.19518
O	Waste of space on site	63	2.9524	0.74001	0.16148
P	Defects	63	2.9524	0.74001	0.16148
Q	Work not done	63	2.9524	0.86465	0.18868
R	Over allocation of materials to an activity	63	2.9524	0.97346	0.21243
S	Unnecessary work	63	2.9048	0.88909	0.19401
T	Poor quality of materials	63	2.8571	0.79282	0.17301
U	Poor storage of materials	63	2.8095	0.74960	0.16358
V	Workers performing activities well below their capabilities	63	2.8095	0.87287	0.19048
W	Abnormal use of equipment and tools	63	2.7143	0.84515	0.18443
X	Inadequate storage spaces	63	2.7143	0.84515	0.18443

Another observation was that, respondents understood waste from the point of view of one or more of the categories of waste but certainly not all. Subcontractors generally preferred to consider excess materials in inventory as locking up their capital rather than waste. They also understood waste in relation to rework. Different from the above explanations, one respondent understood waste as activities carried out that do not add value and lead to loss of time, quality and cost.

Respondents mostly did not define waste with respect to value adding as 57% said it was difficult for them to identify value adding activities. This give rise to situation where contractors are not able to identify all wastes and make them targets for reduction or elimination. Site observation confirmed this position because most Site Supervisors concerns at waste reduction were geared towards the efficient use of materials to prevent them from being wasted. Very little consideration was given to time related waste. From the findings, most activities which are time related such as delays in arrivals, slow decision making by consultants and inefficient movement of workers were usual occurrences on site. On the other hand, activities such as defects, over allocation of materials and work not done, which the respondents considered to generate waste, were not significant to this study, thus giving a clearer picture of the angle from which waste in construction is tackled from.

The above can be explained by the fact that 61.9% of respondents said they had no tools and techniques that helped them identify waste. In the absence of such tools, it only follows naturally that not all activities that generate waste would be captured. Overwhelming majority of 90.5% of respondents said they would like to introduce the concept of lean in their organization to help them identify and eliminate waste. Though most respondents were not familiar with lean concept, after a little explanation, they expressed willingness to adopt such a concept. One respondent, who has some knowledge on lean concept, though accepting to adopt this concept, was particularly concerned about the capital intensive nature of its implementation in the initial stages but agreed that it paid off in the long run. This study however, did not go into the monetary requirements and implications of implementing lean concept in construction.

Identifying value adding and non – value adding activities on site will greatly help in detecting activities that generate waste and subsequently target them for reduction and/or elimination.

5. Conclusion

Clients have become increasingly demanding and require products and services at lower costs, higher quality, shorter execution durations and more reliable schedules. In response to this, industries are reviewing their operations to meet the demands of the end user. In the light of the above, the author sort to study into how supply chain management can benefit the Ghanaian building construction industry through the application of lean concept. Specific areas that were target for study were to assess the level of collaboration and coordination in planning of activities among construction players and the sources of waste in construction.

Waste reduction is the best and usually the most economical of the different management alternatives. To implement an efficient waste reduction programme in the Ghanaian building construction industry, it is necessary to identify what is generating waste and its causes.

To achieve the above, the author through case study approach, gathered data through administering of questionnaires, in depth interviews and direct observation of construction sites on KNUST campus. Data collected were analyzed and the findings gave a clearer picture of the current practices in the construction industry, pointed out areas that needed commendation and those that needed improvement.

Waste is not only associated with waste of materials in the construction process, but also other activities that do not add value. Concepts such as waste and value are not well understood by construction personnel. They often do not realize that many activities they carry out do not add value to the work. These issues contribute to a reduction in the value of construction productivity and could reduce a company’s performance and profitability. By identifying the incidence of waste during a project, construction personnel are able to easily identify the best solutions and ways to apply new technique for reducing the amount of waste, leading to increase project productivity.

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SYSTEM ADJUSTMENTS THROUGH VECTOR ORGANIZATION AND TECHNOLOGY

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Abstract

The production system is in the function of the organization and the technology of an implied system. The organization is the function of the structure and the flow, which in turn defines the unity of the arranged interrelated elements. The use of new technologies, especially the ones from the realms of computer science and cybernetics, and integrating them into the building industry technologies provides for enhancing the building industry business flow indices. The existing organization structure is thus to be supplemented with adjustment tool which is inevitable for systems and provides for business systems to feature the resources/days –based levels of control over projects. IIS technology has thus turned the matrix organization structure of the building industry into the vector one.

The discrete norm elements should be replaced by the vector norm elements for the purpose of speeding up the technologic processes of planning and norm defining that are in turn the motors of companies providing for the deployment of he implied controls (system adjustment, that is); in other words, it means that the BIM business system – or the whole system as well- should be modeled. By means of further modeling and the BIM system simulations, there emerges the building industry business DSP model within the micro unit. The DSP method (dynamic structured programming)) integrates the dynamic and the structu8red programming and provides – for the time being.-for a dynamic modeling of structures and the flow through the formula within the vector system; as to the future, it will provide for defining the organization differential by means of iterating multidimensional model structure.

Keywords: vector organization; vector norm; daily system adjustments; BIM and DSP models;organization differential

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1. Introduction

Each system is a structural unit of single elements and the flow through these elements which, in turn, defines the unity of ordered interrelated parts, i.e. the elements of the system. In the building industry production business system that is so important to us, organization and technology interweave as the two key subsystems that make up the structure and the flow of all the components of the implementation of building industry projects [1]. The already existing subsystems were being created in the course of history and within their specific structures with some of them still giving good business results in some economy and politics systems; however, the production systems aiming at better business indices require a further development of organizational and technological structures. The matrix business structure is considered today to be the most suitable one for building industry. The system control we have known up to now is in turn supplemented with adjustment tool that is inevitable in the contemporary era of cybernetic control [2]. The use of these technologies, especially the ICT and cybernetic ones, and implementing them into the building industry technology provide for upgrading of building industry business results indices and for the defining of the adjustment tool at the level of resources and days, i.e. at the level of the organizational differential. Such daily-based system adjustment provides for IT defining of planning the projects and for reducing risk within projects. [3].

2. Modeling and Adjustments of the System

Modelling and simulation of systems are extremely popular nowadays, especially via 3D and nD as well as via linking systems into BIM systems [4]. The purpose of BIM is handling the information at any time, i.e. the unique information related to a particular day and emerging from a unique integrated information system and from each branch of activities related to the project. By means of mere classic transfer of data from old models into the information system, no advance in business results can be achieved. It also proved to be insufficient if static models are copied into information systems and thus the key problem of the 4th industrial revolution was defined as well. Computers are intended for processing based on cyclic and variable qualities of data mass through functional (algebraic) presentation. This is why the organization and technology of all systems – including the building industry ones- have to be standardized/modeled by means of dynamic nD models in the function of project documentation variables [5]. These models, defined mathematically and in accordance with their algorithmic qualities, will gain positive effects regarding the principles of doing business and the quality of all processes of being administratively accessible. The transfer of the old technology for defining expense list and creating the respective offer into the software system based on the old organizational and technological structures also proved efficient only to a very moderate extent, i.e. it was an obstacle for the development of the whole economy branch. The features of the old static system of norms are linearity, discreteness and a lack of standard of describing the norm process. The description of a process is thus never complete despite comprising initially more than 20000 words, 100000 records and 7000 resources. So, the key problem is the static, discrete norm defined through a mere “parts list” and extremely fixed and inflexible in terms of variability of the project resources dimensions, especially when the new technologies are implied. However, for the purpose of speeding up the technological planning and norm-setting processes for the development “engines” of a company that in turn lead to certain control (modeling) of a system, the discrete norm elements have to be replaced by the dynamic ones. These elements can be model-standardized and optimized, which leads to achieving the goals being set by any business system including the building industry ones as well. Yet, however, the static copying of data teamed with IT indicated a new component of the organization system, namely resource.

3. 3D Vector – Organizational System Structure

The assumption is that the static PBO (project of building organization) should be replaced by a dynamic one, i.e. by model standardization [6] of the building and all other industries by means of deploying 3D organization and nD technology. In that way, the information processing system checks a source as a component and presents the quickly-accessible information as the third component of the organization structure; thus the vector organization structure of the company is created and this is in fact the 3D organization structure. Considering the current development of various business organization structures in the building industry, the mostly preferred one is the matrix organization with a stress on the project implied, a project-oriented organization in other words. Such a financial monitoring system proved to be insufficient for an effective monitoring of the productivity indices, so the structure is supplemented with process-monitoring of projects in order for the obstacles for project implementation are detected as soon as possible. IS –

integrated information system of the building industry executi provides for monitoring of a project down to the level of resource. Thus, the resource axis is added to the matrix axis as the third spatial (vector) structure – Fig 1

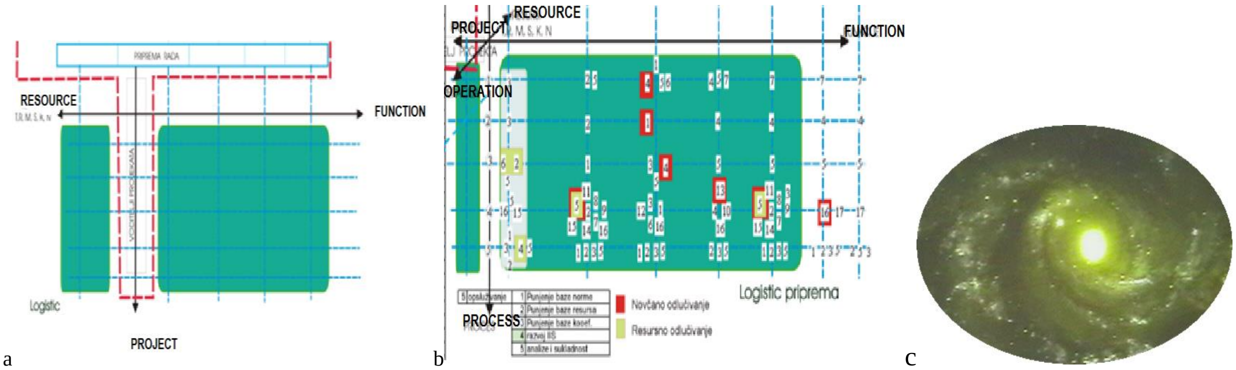

Fig. 1. (a) vector-matrix structure, (b) vector-matrix structure oriented to resources (c) The Universe – Cycle-vector

A further gradual branching of the system from processes to operations, procedures and increments in a coordinate presentation gives an n-dimensional system, i.e. a vector presentation of organization or a building industry system in the work-out of the PBO (project of building organization). By means of breaking down (deduction) of the procedures within the work preparation procedures in envisaging PBO as a logistic function of production, the products of a certain procedure are defined graphically or analytically and they are as well presented in the vector PBO system. These results of PBO are offer, gantogram, histogram, S-curve etc. Fig. 2.

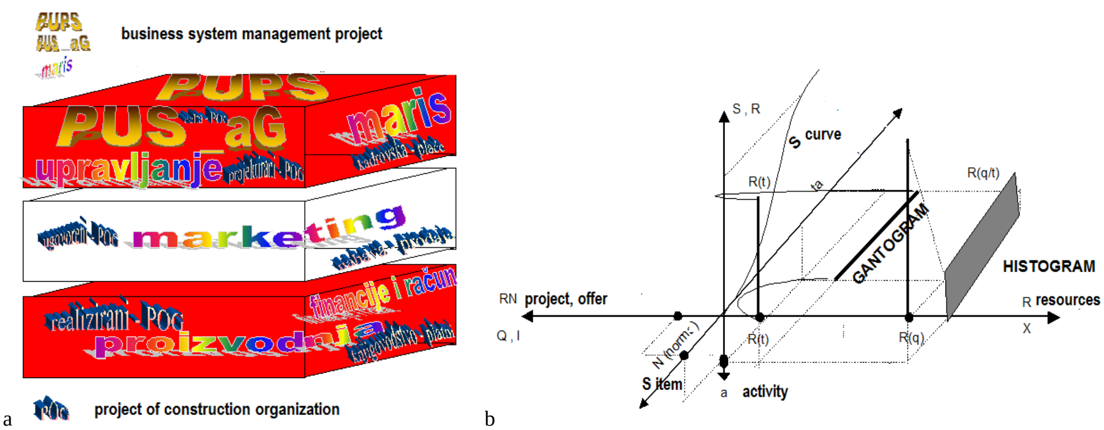

Fig. 2. (a) BIM- IIS PUPS, (b) Vector presentation of work results - PBO

4. 4D , nD – Vector Production System Technology

Similarly, the 4D norm model or vector norm developed from the static norm. Materials and permanent assets are in the function of the constructive and geometric properties of a building industry project within the given technology framework, so the consumption of materials is boiled down to the project documentation dimension by means of relating the constructional equations to the resource efficiency. The results of the relating represent the monograms of the bearing capacity of buildings that at the same time serve as resource norm for the given building. The tendency to make the monitoring of resource shorter and faster created the vector presentation of norm, the vector MSN [7] in other words. The creation of norms in accordance with workers' vocations reduces the quantity of work norm discrete data whereas the model is obtained by defining the functional relation of norm resources and time with the dimension of a building or works. The time norm can be presented as the resource efficiency in the three-dimensional equation. The variables are the elements of technology Y_r , organization Z_o and project construction X_k as shown in Fig. 3.

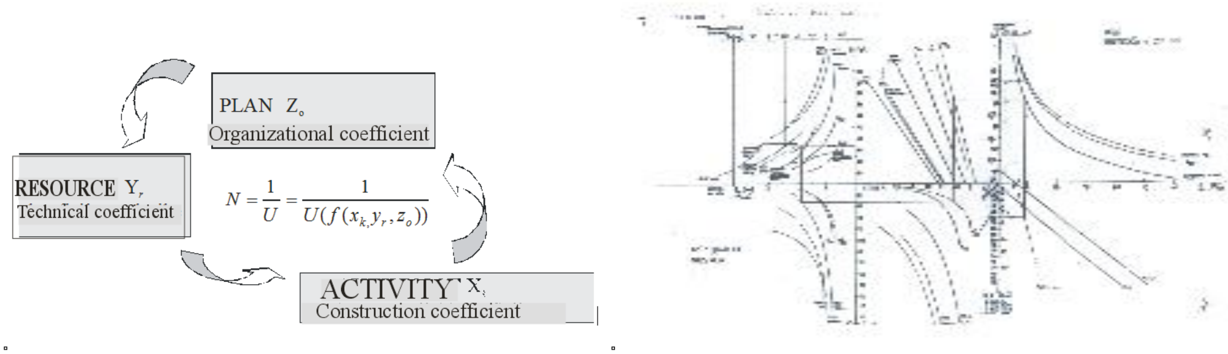

Fig. 3. (a) Vector norm model, (b) vector monogram for concrete formworks technology– Construction Works Company GK Međimurje

The analysis and systematization of the old norms have brought the three-dimensional variables into sight, namely the variables of construction, technology and organization for the purpose of defining the vector norm hypothesis [8] (1, 2).

$$Vektorski\_normativ = N_{k,r,ko_k,kd_i} = kd_i(ko_k(f_0(k,r))) \qquad (1)$$

Based on examples of various technologies, the tables were created in the function of the constructive elements of performance *(k)* and the dimension of that performance element (kd_i) as well as of resource *(r)* which means the performance technology and of organization with defining the basic type of the constructive element (ko_k) representing an organization unit. By means of using these variables, all the static tabular presentations of various systems can be boiled down to the graphic vector presentation. By extracting the constructive element, which is the easiest to define and is thus most frequently used, the basic constructive element is defined *(k)* in dependence of which other construction elements are written down at the given (ko_k). For the purpose of defining the equation for the minimal time-span of the basic constructive element for the discrete values mass given, Gauss least median of squares method is the most feasible as it gives approximations, i.e. it gives the model norm for the basic system. Materials and permanent assets are in the function of the constructive and geometric properties of a building industry project within the given technology framework, so the consumption of materials is, by means of relating constructional equations to the resource effectiveness, boiled down to the project documentation dimension. The results of the relating represent the monograms of the bearing capacity of buildings that at the same time serve as the resource norm for the given building.

$$Vektorski\_normativ = N_{k,r,ko_k,kd_i} = kd_i(ko_k(f_0(k,r))) = \sum_{kd_i} kd_i(\sum_{ko_k} ko_k(\sum_{k} \sum_{r} f_o(k,r)) \qquad (2)$$

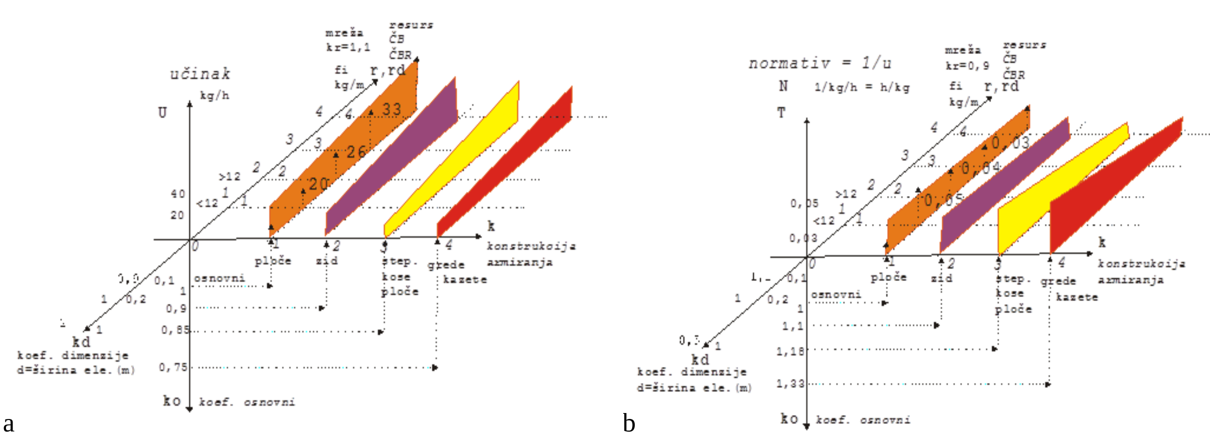

Fig. 4. (a) concrete reinforcing efficiency, (b) concrete reinforcing norm

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5. Model Standardization of nD and DSP BIM System Technologies

The linking and updating of the afore mentioned models by the iteration software technology lead to the development of DSP model that was supported by model solving of the problems related to defining production and products based on operational research [9]. The product is thus PBO and the offer is defined as $P = \Sigma F_n (S_{i,j}) = f (T, O)$, a function of technology (construction) record and the performance technology, whereas $T \approx O = f(A,R,D)$, i.e. as the function of variables A-activities, R-resources and D- the dimension of construction and the performance resources efficiency. The problem of the product "parts list" is solved by vector defining of structures in the dynamic programming manner, where computers appear feasible for this aspect of two- and more- dimensional operations.

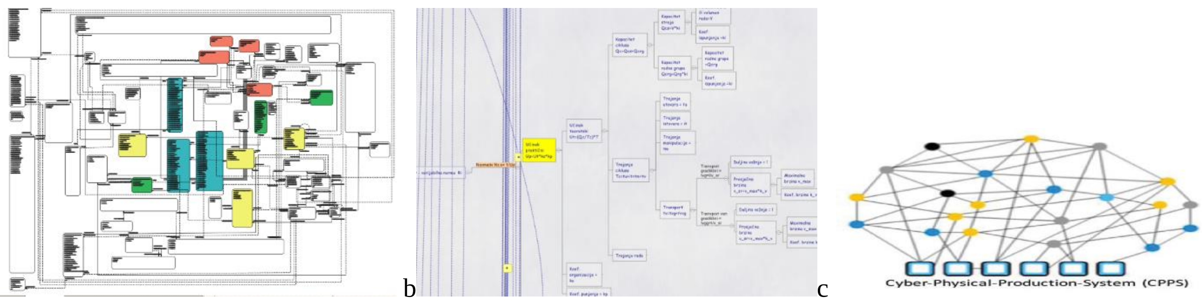

Fig. 5. (a) modeling entity for a computer (nD) (b) modeling of data by MindManager – DSP method (c) Cyber system [10]

This aspect of the technologic achievements dissolving into organizational ones for the purpose of relieving the gap among them results in designing the cyber- physical-productive system model [10,11] with the respective presentation in MindManager [12]. VNS – vector norm standardization fits as well into DSP model when the vector or variable norm model is included in the organization matrix and dimension submatrix (3).

$$\left[T_n\left[O_n\left[ke, jm, k, c, v\right]_n\right]\right] = \left[T_{n+1}\left[O_{n+1}\left[ke, jm, k, c, v\right]\right]\right] \tag{3}$$

A further simulation of the afore mentioned models by means of the cybernetic Cro-Podturen equation [13] provides for describing various states of the system (4).

$$K = U\begin{bmatrix} n_1 \to k_{\max} - 1 \\ n_{\max} \downarrow \end{bmatrix} U \begin{bmatrix} n_2 \to 1 \\ n_1 - k_i \downarrow \end{bmatrix} U \begin{bmatrix} n_i \to n_i + 1 \downarrow n_k - 1 \\ n_1 - k_i \downarrow \end{bmatrix} U \begin{bmatrix} n_k \to n_1 + 1 \\ n_{\max} \downarrow \end{bmatrix} \tag{4}$$

The deployment of system elements state probability in the given model leads to Markov and DSP stochastic models that can define a project based on time and expenses and the variables define the risk level for the project. Modified Gauss equation (5) is a prototype for the real S-curve in the function of T and x or t. For that purpose, more data from the field are required, the suggested linear models should be studied and coefficients (a,b) have to be defined with a highest possible level of preciseness and probability (5) Fig.6.

$$skvG(x,T) = \lambda kv * \int_0^x \frac{1}{(aT+b)*\sqrt{2\pi}} * e^{\frac{-(x-\mu)^2}{kv*(aT+b)}} dx \tag{5}$$

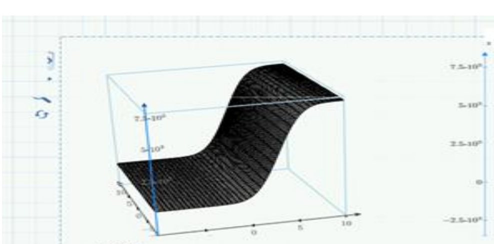

Fig. 6. Modified Gauss curve on existence of a project in time and expenses variables

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6. Conclusion

The response to the problem of informatizing of building industry production is the deployment of model production standardization. Mathematical modeling or vector modeling creates n-dimensional modeling of various processes. In line with shaping the constructors' physical phenomena mathematically, modeling (mathematicising) of business systems as organizational components is more and more common today. A further cyberneticizing and softwarizing of the organizational cybernetic models create models that are easy for computers to process, This has given a new momentum to the research in the risk of doing business field thus defining the probability of processes taking place through defining uncertainty or consequences. This aspect of the technologic achievements dissolving into organizational ones for the purpose of relieving the gap among them results in designing the cyber- physical-productive system model. The objective of the modeling and standardizing method is to define the processes of building industry products as accurately and precisely as possible. The intentions of the building industry are modeling of project implementation "just in time" and adjusting the production system and the business system as a whole in a way that provides for monitoring and controlling a project on daily basis, i.e. daily monitoring. DSP method of updating through the cybernetic and combinatory approach may as well change the classic operative research scientific branch and it is thus recommended that new state and EU interest norm projects should be started concerning the detection and defining of the development of standardizing technologies and organizations. Defining these models means a lot of ceaseless work that requires upgrading the states of science and economy. The final result is to spur on new discoveries in the fields of developing standards of technologies and organizations, relieving the gap among them through so-called software mathematics and stipulating an increased level of utilizing BIM principles in processes of business operations.
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The Future Role of Facilities Managers in an Era of Industry 4.0

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Abstract

The job description of asset and facilities managers continue to evolve. The future roles of facilities managers is somewhat a concern, given the trend and progression of innovative technologies in recent times. This study sought to evaluate the perceptions of built environment practitioners, involved in management of infrastructure during operations, regarding the influence of technological innovation on the future roles of facilities managers in terms of sustainability. An interview guide was used to solicit information regarding the future roles and responsibilities of facilities managers. The interviews were conducted with five facilities management practitioners selected purposively and conveniently based on knowledge, willingness and ability to participate in the study. Themes on the influence of innovation on facilities management practice and future adaptive roles of facilities management were evinced. These findings are envisaged to be useful in developing new strategies and directions to equip and accord facilities managers with the necessary techniques to adapt in this ever-changing era of technology and innovation.

Keywords: Facility mangers, innovation, Johannesburg, technology.

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1. Introduction

Facilities management as an industry has its roots as far back as the 1970s in the United States and the 1980s in the United Kingdom and Europe [1]. Globally, the facilities management sector is worth $1.1 trillion per annum, in economic terms [2]. In the United Kingdom alone, the sector is reportedly worth more than $1.0 billion yearly [1]. Increasing awareness of and appreciation of facilities management has led to an exponential growth of the industry globally, which is now worth an estimated $900 billion, with an annual compounded growth of over 8% expected by 2025 [3].

Facilities management is a strategically integrated approach to maintaining, improving and adapting building and support services of an organisation in order to create an environment that strongly supports the many objectives of the organisation. This inter-disciplinary field is also devoted to the management and coordination of space, infrastructure, organisation and people. Therefore, facilities managers are authorities in the built environment industry.

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Typically, the duties of a facilities manager entails general upkeep and management of facilities, refurbishments, budgeting and cost control, record-keeping, project management, and others. Overall, facilities management supports business value and contributes to the delivery of an organisation's strategic and operational goals, both in the long and short run [4]. The facilities manager's job title may therefore differ in different organisations. However, with the continuous innovation and development of facilities constantly under pressure to reduce costs and at the same time add value to an organisation, the role of facilities managers has continued to evolve. Other challenges faced by the facilities management industry globally include workplace changes, occupational health and safety and reporting requirements, information systems management needs, cost-effectiveness, integrated facilities management services and innovation [2]. The situation is somewhat compounded by technological advancement and digitalisation fervour that the fourth industrial revolution (4IR) era has brought.

The 4IR is where the tools of technology can become literally embedded within us and even purposefully change who we are [5]. It brings about innovation that risks creating forms of conflict. This suggest that all stakeholders have to work together to improve innovative governance and commercialisation approaches, which synergise with the current and emerging technologies. The fourth industrial revolution, which is characterised by the fusion of technology that continuously builds and extends the impact of digitalisation in everyday life and applications, can play a role in ensuring sustainability of the facilities management role. The technology-driven changes and advances, which merge the physical and digital worlds, can create both huge promise and potential peril, but it forces a rethink on how organisations create value [6]. Therefore, continuous research on how facilities management can be sustained in future requires attention.

Previous studies on the trends and predictions of the facilities management practice have focused on issues around the pros and cons of in-house versus outsourced management models and the innovative nature of the outsourced model [7]. Other research have included biological and environmental initiatives that tally with the 4IR to improve productivity [8], [9]. Other studies focused on the changes and associated challenges in facilities management practice, at the corporate and government levels in Malaysia [10] and ways to improve preparedness in facilities management practice by increasing awareness of the facilities management career path, and thus the number of professionals [11]. On his part, [1] espoused that one of the ways to improve the facilities management sector standing is through the creation of more industry standards and benchmarks. This can partly be achieved through alignment of standards with developing circumstances. Innovation is high on the agenda in many economies in terms of facilities service delivery, and this is aimed at producing organisation, environmental and technological product innovations. Hence, concerns abound regarding the transformation that the 4IR brings. The 4IR brings unpredictability to the future of work, requiring people's opportunities and well-being to be localised and re-examined [9]. Therefore, the objective of the present study was to investigate the role of the facilities manager given the changing times of new technology and innovations. The findings of the study are envisaged to be beneficial to facilities management practitioners in identifying ways to create an enabling and innovative environment for practice.

The next sections of the current paper present an overview of the facilities management practice and the role of technology in the practice of facilities management. The findings from interviews conducted among facilities management practitioners are presented thereafter and the conclusion drawn from the findings follows.

2. Literature review

2.1 Facilities management roles – An overview

Facilities management is the integrated management of the work environment and supporting services of organisation to provide an enabling environment to achieve a business' primary objectives [12]. The post of facilities manager is both administrative and supervisory. According to [13], facilities management encompasses multiple disciplines to ensure functionality of the built environment by integrating people, places, processes and technology. [14] defines facilities management as "enabler of sustainable enterprise performance through the whole life management of productive workplaces and effective business support services". The International Organisation for Standardisation

(IOS) defines facilities management as a function which integrates people, place and processes within the built environment with the purpose of improving the quality of life and the productivity of the core business [13], [15].

The facilities manager's title may differ depending on the organogram of that particular organization. Some of the titles include Facilities Manager, Head of Facilities, Facilities and Support Services Manager, Area Facilities Manager, Corporate and Real Estate Services Manager, Facilities Technical Manager, Facilities and Purchasing Manager. These job responsibilities cover various aspects including customer service, environmental issues, project management, and space management, building fabric maintenance procurement, financial management, information management, risk management and others [16]. The facilities manager is duty-bound to sectionalise aspects into management of services, outsourcing, performance measurement, life cycle costing, budgeting and cost control, setting up and maintaining database, environmental complain auditing, and monitoring project processes to aid management at the operational stage. Today's facilities management focuses on organisation's core business and contributes to its bottom-line by reducing costs, improving productivity, generating revenue, and improving its image. However, the future scope of facilities management is considered taking into account organisational factors, current conditions and the impact of future innovation and change. The impact of these factors is reviewed in the next section.

2.2 The future of the facilities management practice and the fourth industrial revolution

In the facilities management world, the roles change with time as customer expectations change regularly. Figure 1 presents the roles of facilities managers over time. From the 1990s, the practice of facilities management has evolved from being just service provider to a business enabler, including functions based on imperatives such as "integrating", aligning" and "innovative" (Myeda, 2014). The future generation is therefore faced with more freedom and flexibility and a lifetime of learning and innovation, requiring a change in priorities [4], [17].

Figure 1: Facilities management roles' evolution over time (Source, Myeda, 2014)

Certain factors therefore shape the way facilities management services are delivered. These factors include culture, technological development, current economic conditions, sustainability considerations, health and wellbeing, innovation, and others.

- Workplace culture – The workplace culture to promote corporate identity and foster more efficient collaboration and knowledge sharing is important.
- Technological advancement – The influence of technological advancement has already been felt within the operations of facilities management [8]. Integration of intelligent and digital technologies such as BIM and robots may be expected to carry out some of the functions associated with facilities management in future. The use of more efficient information management systems to store and retrieve data is beneficial. It is vital for organizations to use computerised systems to enhance information transfer and communication to record and monitor costs, for financial budgeting and control.
- Current economic conditions – When economies face hardships, there is greater pressure to maximize value. The more economies struggle, the more competition organisations face.
- Sustainability considerations – The need to incorporate factors such as climate change and energy efficiency of buildings is recognised.
- Health and wellbeing – The focus here is on artificially and technologically advanced human capabilities, which create significant impacts on the facilities management and service industry.
- Innovation – This has become imperative in facilities management practice given the need to improve on corporate image and identity and achieve competitive advantage. According to [7], there is no way around technology and thus innovation has to be a key component of the facilities management business. It is extremely pertinent if a company wants to add value for the clients.

The above factors are envisaged to influence the continual changes which facilities management companies face and which in turn determine the functions they perform. The rate at which people adapt to changes in their work environment depends on the quality of enabling infrastructure and skills development [18]. This suggests that the changes which the 4IR brings will require equipping future facilities management practitioners with the requisite skills needed to face any challenges they might encounter.

The fourth industrial revolution is characterised by the integration of technology that continuously builds and extends the impact of digitalisation in everyday life and applications, can play a role in ensuring sustainability of the facilities management practice [6]. The 4IR refers to how technologies like artificial intelligence, autonomous vehicles and internet of things are merging with human beings [19]. It is characterised by the convergence of the physical, digital and biological worlds and adds an unpredictability dimensionality with the speed of technological advancement [9].

The fourth industrial revolution has the potential impact of promoting predictability and transparency in risk preparedness and responses [18]. The 4IR provides conditions for innovative sustainable inclusion and economic growth, shared prosperity and decent work for all, taking into account different level of development and capacities should be created [20]. 3D printing can better inform decision-making on infrastructure and energy-efficient buildings. Drones can be used to deliver urgent and reliable information on hard-to-reach areas in buildings [18]. Technological advances are drastically changing how individuals, companies, and governments operate, ultimately leading to a transformation, like the previous industrial revolutions. In fact, studies show that technologies will eliminate some jobs, while creating demand for new jobs and skills and this may as well be a source of peril to facilities management practice, as with some other professions [19]. These predictions that automation and technologies will make humans redundant dates back to the First IR, when textile workers protested that machines and steam engines would destroy their livelihoods [21]. This view was however, not shared by [22], in which it was opined that the creation of jobs will be much greater that the destruction of jobs. However, it is critical for facilities management practitioners to harness these technologies in achieving efficiencies and adopting best practices [7]. A company's most important asset is its creative capital, which are the employees who pioneer new technologies, create new industries and structures and drive economic growth on a larger scale [21]. However, without adequate prepared human capital, a country will not be able to harness new technologies [22].

Research reveals that some countries and sectors are unprepared for the 4IR. A study of 10 global cities' readiness to adopt new technologies in Singapore, revealed that only 42% of the surveyed respondents felt ready to adopt new technologies [18]. Industries in South Africa, including the facilities management sector, are not prepared for the 4IR [22]. However, the 4IR, a combination of technologies, is here to stay and has been for a long time. For instance, there is the internet of things (IoT), which is the inter-connective network of physical objects including devices, building, vehicles, software, sensors and others, which allow remote controlling of objects [21]. Therefore, continuous attention to ways of adapting and integrating these new technologies is critical.

3. Methods

A qualitative approach was adopted for the study. Interviews were conducted with five facilities management practitioners. The participants were selected based on convenience sampling of facilities management departments in three organisations, including the university's facilities management department, a hospital and a private facilities management company in Johannesburg, South Africa. Purposive sampling techniques was also used to identify respondents based on their knowledge, willingness and ability to participate. The participants were approached during working hours and requested to participate in the study. Therefore, participants who were willing and able to participate in the study were selected.

The information collected was based on the perceptions of the respondents on the future focus of facilities management practice. The empirical data was analysed using thematic content analysis to identify emerging themes with regard to the changing roles of facilities managers. Themes on the influence of innovation on facilities management practice and future adaptive roles of facilities managers were evinced. The findings are presented hereunder.

4. Findings and Discussion

The participants' perceptions on the future role and responsibilities of the facilities manager in future given the intense pressure brought about by the 4IR. Findings revealed that there was a view that facilities managers will still be required to create value for their clients. This was evinced in statements by the respondents:

> *"The current change of the industry …the future facilities managers will be required to be able to design a service delivery system focused on what is creating value to the core organization and how to engage frontline employees….Providing better service experience will become critical success factor for the future facilities management.'*

> *"The role of the facilities manager is to target on discovering and defining what it means to create value in the organisation, whether by researching the core organisational goals or understanding government priorities…there are no exact future roles, however, to prepare for the future, they constantly have to adopt a greater role as investors and strategic partners as the demands of their organisations will further exceed their capacity to deliver in-house…Future roles are based on the combination of value of the organisation and design workforce…"*

> *"Facilities managers today are expected to understand their companies' core business strategies and contribute to the bottom line, not only by reducing facility costs, but also by improving productivity, generating revenue and image of the organisation. Future facilities mangers should be looking into the sustainability of the industry and how it is going to bring changes….'*

These statements suggest that service should be at the core of any facilities management system and focus in future will be on optimising customer service quality and sustaining the profession, and this will require equipping facilities managers to prepare for future demands and capacities [22].

In the words of another respondent:

> "…*facilities management as an industry needs to think its approach and needs to stay competitive and there are still many efficiency gains to be achieved"*.

This implies that in order to maintain competitive advantage, while benchmarking against best practices, which is important in facilities management, organisations need to constantly review their approaches in practice.

It was also found that the 4IR could help in incorporating sustainability considerations in facilities management practice. According to respondents:

> *"Future facilities managers should be looking into sustainability…and how it is going to bring changes….global warming …and with the need to change to more sustainable options, facilities managers and service industry can expect the 4IR trend to affect the supply chains as well as building design, management and maintenance…systematic design will become more and more important because of technological advances…"*

> *"Facilities managers will be challenged to control and co-ordinate new environments…and more innovations…."*

There is the use of the IoT and virtual intelligence, and drones, which are innovative tools that can allow easier and more reliable information gathering and recording [21], [23].

Further findings revealed that the future of the facilities manager would entail being proactive in undertaking their functions, as stated by one of the respondents:

> *"The facilities management of the future will be proactive and empowering rather than reactive and constricting"*

This emphasizes the need to equip the future facilities manager with the necessary skills to be able to face the challenges of the 4IR. Managing the change will require a new model of education, complete with targeted programs for teaching facilities managers' new skills [7]. The real opportunity is to look beyond technology and find ways to give the greatest number of people the ability to impact their families, organisation and communities [6]. Organisations need to ensure that they invest in the enabling technological infrastructure and skills to make sure that they are not left behind [18]. Therefore, awareness and skills should be impacted in higher institutions and training of staff members to acquire skills beyond basic digital literacy. The implications for the facilities managers and the real estate sector as a whole, are that digital technologies will require soft skills and applied creativity in performing functions involving customer interaction, and service delivery enhancement [21].

5. Conclusion

The study set out to investigate the perceptions of facilities management practitioners on the impact of the 4IR on facilities management practice. The future sustainability of the facilities management profession is a concern given the unabating impact of technological advancement. The findings revealed that the main concern was on the continued delivery of services to the clients' satisfaction, as well as the upskilling of employees to be able to harness new technologies.

The findings of this study are envisaged to encourage the training and upskilling of facilities management practitioners to be able to integrate and adapt new technologies and tools in current processes and functions. This will ensure that they are not left behind in this era of the 4IR. Opportunities to train and upskill facilities managers should be embraced. Facilities managers should continue to partake in delivering sustainable development goals in the era of the 4IR.

The current study's small sample limits the generalization of the results. However, findings give useful insight on how facilities management practitioners perceive the impact of 4IR on their profession. Further studies are on-going, which includes other practitioners in the built environment industry, in order to obtain more generalisable findings.

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The Impact of Construction Dispute on Projects in the Mpumalanga Province of South Africa

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Abstract

Construction disputes have a greater effects on the construction industry as opposed to other industries. Especially negative effects are prevalent on the project participants which lead to poor execution of the project. The study investigated the impact of disputes in construction projects in the Mpumalanga Province. The data used in this paper were derived from both primary and secondary sources. The secondary data was collected via a detailed review of related literature. The primary data was collected through a survey questionnaire which was distributed to project participants. Out of the 90 questionnaires sent out, 80 were received back representing 89% response rate. Data received from the questionnaires were analysed using descriptive statistics procedures such as Ms Excel and SPSS software. Findings from the study revealed that; bad relationship between parties, loss of productivity, cost and time overruns, loss of company reputation, loss of professional reputation delayed payment and rework were the main effects of construction disputes in construction projects. Therefore, construction dispute have an effect on most of the project participants which may lead to poor execution, reduced profit margins and budget escalation. Hence Dispute must be resolved as soon as possible to avoid mostly all the effect they have on projects and stakeholders. Furthermore, risk have been identified to be associated with construction dispute, if risk are well managed the occurrence of construction dispute will be reduced.

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Keywords: Construction Industry; Construction Projects; Impact; Mpumalanga Province.

1. Introduction

Disputes are prone during construction due to the problem of contractual terms such as payment, variation, and extension of time and the unavailability of information [1]. Construction Projects are often delivered under a complex and uncertain environment, with claims being an inevitable part [2]. Construction disputes materialise when construction claims are not settled in an effective, economical and timely manner [3]. However, resolving disputes can be expensive and time consuming. It is therefore, crucial to manage disputes proactively to ensure that early settlement is achieved [4]. Any stakeholders in the construction project can generate dispute (including client, professional consultants, contractors, subcontractors) through their level of knowledge of the construction process. Furthermore, the more complex the project is, the higher the probability of dispute causation [5]. Disputes have become an endemic

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feature of the Mpumalanga construction industry. Hence, this research aims to investigate the causes of disputes in construction projects in the Mpumalanga Province of South Africa.

2. Construction Industry

The construction industry (CI) in many countries is a key component of economic growth. Furthermore, the construction industry plays even a greater role in development and poverty alleviation by providing access to basic services and transport facilities in the developing countries [6]. The CI is an important sector of the economy because of the outputs of its activities [2]. It contributes to national socio-economic development by providing the buildings which are used in the production of all goods in the economy. The CI is one of the most diverse and unstable sectors within the economy [1]. It faces fluctuation demand cycles, project- specific product demands, uncertain production conditions and it combines a diverse range of specialist skills within geographically dispersed short term project environments [3]. However, anything that impacts on construction industry has potential to affect the whole economy. Since, it's unique and complex to other industries and it involves many participants in all trends, due to this, conflict and disputes can easily occur for example; through changes in plans, quantities, or details of construction which are inherent in the nature of construction [7].

3. Disputes in the construction industry

The occurrence of construction disputes can lead to negative impact towards client organisation, furthermore, carelessness and negligence in construction has risen to greater prominence [1]. Dispute between client and contractor will impact work progress since it will be slow, subsequently, the cash flow suffers terrible [3]. Construction is procured and completed in a manner which lends its self to numerous potential disputes. The procurement process includes an owner's version, selection and completion of a formal design, selection of a construction team which usually includes many specialist subcontractor and suppliers sometimes, and ultimately building commissioning and turnover [4]. Depending on the type of facility constructed, the whole process can take years. During these time personnel will change, the economy will change and technology will change. With almost 100% certainty, that won't change is the fact that something will not go according to plan during the project and dispute will arise [8].

4. Disputes defined

Dispute is the opposition of interest, values or objectives and is the formation of a position to maintain conflict [9]. Furthermore, dispute according [10], can be viewed as a class or kind of conflict that requires resolution. Another definition according to [1], dispute does not exist until a claim has been submitted and rejected, a claim being a request for compensation for damages incurred by any party to the contract. Dispute is a problem or disagreement between the parties to a contract, that cannot be resolved by on jobsite or on-site project managers [11]. Many authors argue that the most common protracted dispute arises when a contractor make a claim for an increase in the contract sum which is rejected by the project managers and the contractor formally notifies that it does not accept the decision by the project manager. Dispute can be caused by negligence in understanding the terms of the contract for example dispute on misunderstanding and disputes on interpretation of clauses [12].

5. Risk and uncertainty

According to [13] as cited by [6] claimed that construction projects are sensitive to risk and construction risk are associated to construction dispute. The risk listed below can be found in a normal construction contract and they are associated to causes of dispute. According to Zack [13], risk are allocated well in the construction contract such as capability – Physical risks, act of God, suspension of works, untimely responses, union strike, engineering and construction risk, changes, contractor furnished equipment/ material , continuation of work, coordination, defective contract documents, interpretation of requirements, means and methods of construction, owner furnished equipment materials, permits and licences, productivity, site safety, work quality, impractical /impossibility, latent site conditions, quantity variations, site access, weather, capability related risks, defective works, labour forces, subcontractor, supplier failure, economic risks, bonding, contract termination, cost escalation, economic disaster, failure to pay, insurance, project funding, taxes, time related risks, acceleration, delays and disruptions and early use of facility. Therefore, comparing these risk factors with causes of dispute in the table below it is noticed that these risk are included as causes of dispute. Furthermore, this propose when risk surface in a project and are not cured correctly the risk will give rise to dispute. Hence, risk allocation may be achieved through the combination of risk retention, risk avoidance, risk reduction or by transferring the risk to any party that has competency and expertise for best assessing, managing and minimizing it [14]. Therefore risk management is highly recommend in the dispute avoidance [15].

6. Causes of disputes in the construction industry

6.1. Summary of dispute causation

The construction industry is a complex and competitive environment in which participant with different views, talents and levels of knowledge of the construction process work together [1]. Hence the construction value chain means more business interaction and arguments, whether contractual or social, resulting in an increase in the number of construction disputes [11]. Table 1 summaries the cause of disputes.

Table 1: Causes of disputes in the construction industry (Adapted from Kumaraswamy & Yogeswaran [11]

Categories of disputes	Causes of disputes	Authors
Owner related	Variations initiated by the owners Change of scope Late giving of possession Acceleration Unrealistic expectations Payment delays	Blake Dawson Waldron (2006), Kumaraswamy (1997) and diekman et al. (1994)
Design related	Design quality Inadequate/ incomplete specification Quality of the design Availability of information	Blake Dawson Waldron (2006), Yiu and Cheung (2004), Kumaraswamy (1997) and Conlin et al., (1996)
Contract related	Risk allocation Different interpretations of the contract provisions Ambiguities in contract document Other contractual problems	Blake Dawson Waldron (2006), Yiu and Cheung (2004), Kumaraswamy (1997) and Conlin et al., (1996)
Contractor related	Financial failure of the contractor Delay in work progress Tendering Quality of works Technical inadequacy of the contractor Extensions of time	Blake Dawson Waldron (2006), Yiu and Cheung (2004), Kumaraswamy (1997) and Conlin et al., (1996)
Human behaviour related	Adversarial/ controversial culture Lack of team spirit Team spirit	Blake Dawson Waldron (2006), Yiu and Cheung (2004), Kumaraswamy (1997) and Conlin et al., (1996)
Project related	Site conditions Unforeseen changes	Blake Dawson Waldron (2006), Yiu and Cheung (2004), Kumaraswamy (1997) and Conlin et al., (1996)
External Factors	Weather condition Legal and economic factors Fragmented structure of the sector	Blake Dawson Waldron (2006), Yiu and Cheung (2004), Kumaraswamy (1997) and Conlin et al., (1996)

From the above table it is evident that the root causes of dispute they are more or less the same from different countries and are associated with risk. Moreover, the study on dispute clearly shows how big and diverse the construction industry including the culture. Therefore, risk if timely managed well the occurrence of dispute could be minimised and also risk must be transferred to a party that is competent in assessing, analysing and minimize them. The following table will list the contributors to construction dispute.

Table 2: contributors to dispute

Contributors to construction dispute	sources
People, process and product	[16]

Management, culture, communications, design, economics, tendering pressure, law, unrealistic expectations, contract and workshop	[17]
Technical, legal and managerial dispute issues must have a contractual reference	[18]
Construction contracts and unpredictable events	[19]

7. Effects of disputes in construction companies

Construction disputes affect all stakeholders and contribute to inequitable mode of project delivery such as reduced margins, increased costs and even reduced the quality and levels of service [2]. Most disputes which are of minor nature should be settled quickly, fairly and amicably by the construction team [20]. However, from time to time, more serious issues come into disputes and when this happens the building team should make means to reach a fair settlement by negotiation or other means of dispute resolution mechanisms available which are mediation, arbitration, amongst others. The consequences of construction disputes will not benefit the stakeholders in the construction project [3]. Moreover, disputes may affect cash flows (disputes, affect insurance coverage (liability risk exposure), insurance rates (indemnity payment and cost of settling claims), overheads (personal time to defend and settle, plus attorney's fees) and reputation (publicity from large suits) [21].

Therefore, the effects of construction disputes in an organisation can be summarised as follows:

- Loss of productivity
- High tender prices
- Loss of professional reputation
- Loss of company reputation
- Time delays
- Cost overruns
- Cash flow
- Insurance coverage
- Liability risk exposure
- Additional expense in managerial and administration
- Possibility of litigation cases
- Loss of business viability
- Loss of profitability
- Extended and/ or More complex award process
- Break down in cooperation between parties
- Diminution of respect between parties and deterioration of relationship and break down in cooperation
- Additional expense in administration
- Rework and
- Relocation cost for men, equipment and materials

Since some disputes are not avoidable, proper management of conflict and risk will ease the effect it has on the construction process, however resolution should follow quickly. Disputes have a greater effect on the construction projects as opposed to other industries. Construction disputes have an effect on most of the project participants which may lead to poor execution of the project, for example, reduced margins, budget escalation and low quality of work [21].

8. Research Methodology

8.1. Research area

Mpumalanga means the place of the rising sun and people are drawn to the province by its magnificent scenery, fauna and flora. The province is the second smallest province in South Africa yet it has fourth –largest economy. It's situated mainly on the high plateu grasslands of the middleveld. Mpumalanga has network of excellent roads and railway connections thus making it highly accessible [22]. The province is a tourism destination and it's a home, of over 4 million people, the principal languages are siSwati and isiZulu. The province is a summer-rainfall area divided by the escarpment into the Highveld region with cold frosty winter and lowveld region with mild winters and subtropical climate. Mpumalanga is the second largest citrus producing area in South Africa and is responsible for one third of the country's export in oranges. Mpumalanga is very rich in coal reserves. The province house the country three major power stations, of which are the largest in the southern hemisphere [22].

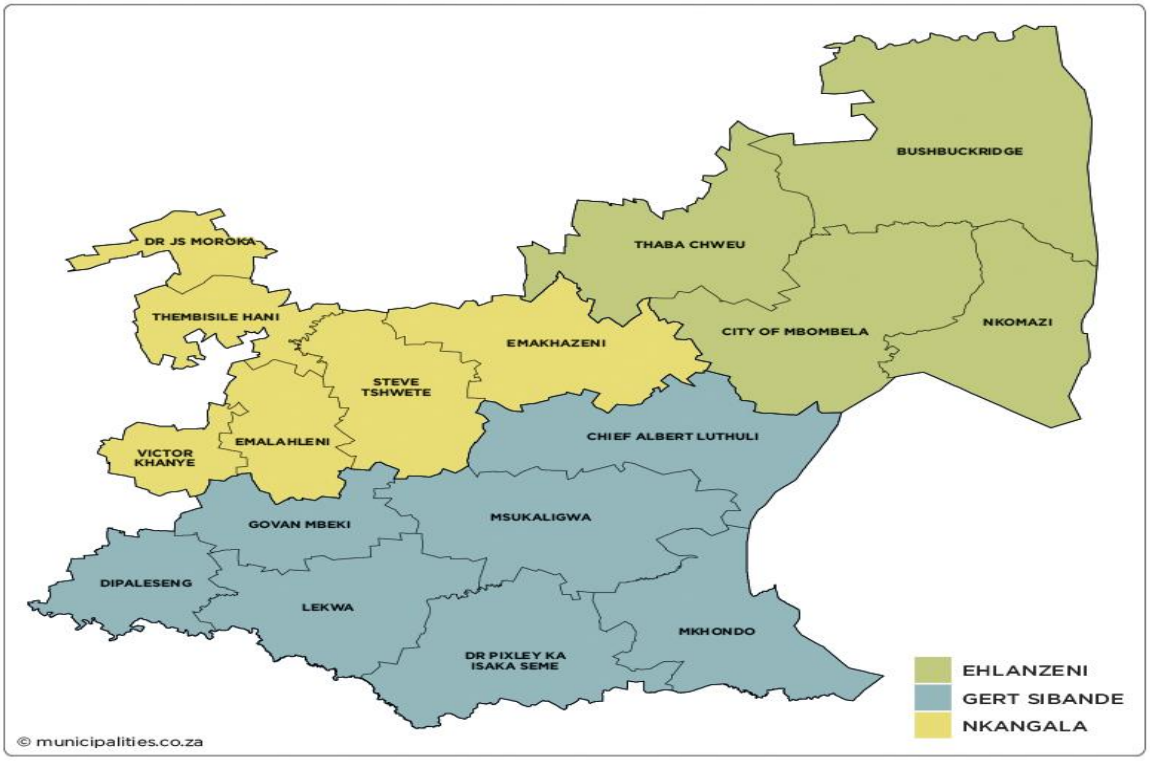

Figure 1: Mpumalanga map

8.2. Research approach and design

Quantitative approach method was adopted to investigate a stakeholder's perspective on the impact of disputes in the construction industry of Mpumalanga Province of South Africa. The study was carried out in Mpumalanga Province of the Republic of South Africa. 90 Questionnaires were distributed and 80 were brought back which were all valid and usable. A well-structured questionnaire was distributed to different construction companies in Mpumalanga Province, amongst construction professionals such as civil engineers, project managers, directors, quantity surveyors, construction managers and contractors who are register on the CIDB data base. The questionnaires were sent via e-mails, some were delivered to the known construction companies by the researcher and some were distributed during site clarification meetings of contractors and consultants bidders in Mpumalanga Province. The study was conducted from reliable scholarly sources such as articles, journals, books, publications, websites and site experience on the field.

8.3. Statistical package for the social science (SPSS)

The quantitative data collected was analysed with Statistical Package for the Social Science (SPSS) a computer programme which is used for analysing data concerned with social phenomena. The software was used to generate various statistical, including descriptive statistic, which provides a basic summary of all variables in the data [23]. The benefits of using SPSS is that it allows for scoring and analysing quantitative data at speed and it can also be used to perform multivariate analysis. SPSS also helps to present the data in a logical format [23] thereby reducing time spent on calculating scores. However, accuracy in results is highly dependent on inputs, hence the need to accurately capture data from the questionnaire.

8.4. Point linkert scale

5- point linkert scale was adopted for the study which gave a wider range of possible scores and increase statistical analyses that are available to the researcher. The first linkert scale read is on agreement form as follows:

1- Strongly Disagree (SD)
2- Disagree (D)
3- Neutral (N)
4- Agree (A)
5- Strongly Agree (SA)

The second linkert scale read is on likelihood as follows:

1- Extremely Unlikely (EU)
2- Unlikely (U)
3- Neutral (N)
4- Likely (L)
5- Extremely Likely (EL)

The 5 point scales were transformed to mean item score abbreviated as (MIS).

8.5. Computation of the mean item score (MIS)

The computation of the mean item score (MIS) was calculated from the total of all weighted responses and then relating it to the total responses on a particular aspect. The mean item score was adopted to rank the factors from highest to lowest. The Mean Item Score (MIS) is expressed and calculated for each item as follows:

$$\textbf{MIS} = \frac{1n1 + 2n2 + 3n3 + 4n4 + 5n5}{\sum N} \qquad (1)$$

Where;

n1 = number of respondents for strongly disagree
n2 = number of respondents for disagree
n3 = number of respondents for neutral
n4 = number of respondents for agree
n5 = number of respondents for strongly agree
N = Total number of respondents

9. Findings

9.1. Risk factors contributing to construction dispute

Figure 2 reveals that 45% of respondent strongly agree that once risk surfaces or appear in a project dispute will definitely occur, 21% of respondent agree, 9% of the respondent are neutral, 14% disagree and 11% of the respondent strongly disagree.

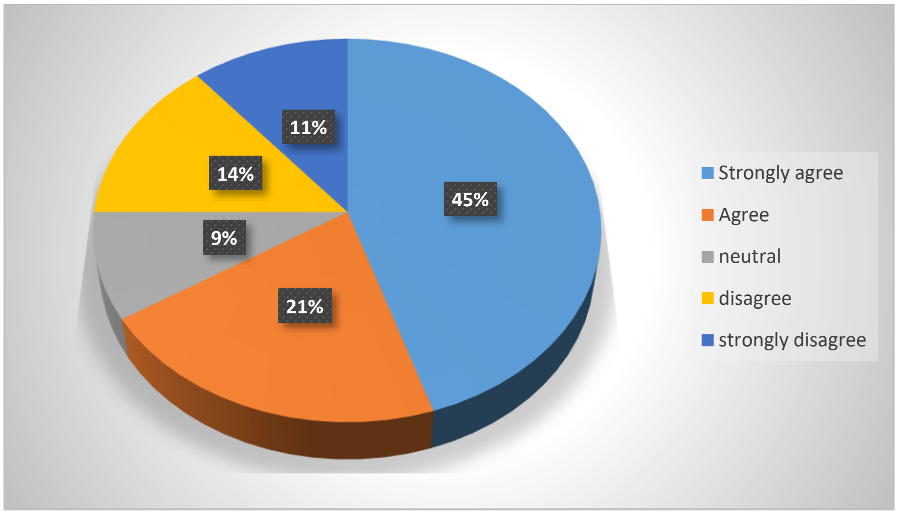

Figure 2: Risk factor contributing to dispute

9.2. Effects of disputes in the South African construction projects

Table 3 reveals the respondent's ranking of effects of disputes in Mpumalanga province, South Africa. Loss of profitability was ranked first with (MIS=4.41 & STD=1.125); followed by Break down in cooperation between parties which was ranked second with(MIS=4.38 & STD=1.104); Loss of business viability which was ranked third with(MIS=4.36 & STD=0.995); Loss of professional reputation which was ranked fourth with (MIS=4.33 & STD=1.130); Loss of productivity was ranked fifth with (MIS=4.25 & STD=1.025); Cost overruns was ranked sixth with (MIS=4.19 & STD=0.938); Time delays was ranked seventh with (MIS=4.02 & STD=1.138); Loss of company reputation was ranked eighth with (MIS=3.98 & STD=0.897); Rework/ repetition of work was ranked ninth with (MIS=3.96 & STD=1.064); Additional Expense in administration was ranked tenth with (MIS=3.78 & STD=0.989); Diminution of respect between parties was ranked eleventh with (MIS=3.69 & STD=1.093); Relocation of Equipment was ranked twelve with (MIS=3.62 & STD=1.175); Relocation of Material was ranked thirteen with (MIS=3.56 & STD=1.114); Relocation cost of workers/ labors was ranked fourteen with (MIS=3.48 & STD=1.094) and Additional Managers cost was ranked last with (MIS=3.43 & STD=1.058).

Table 3. Effects of construction disputes

Factors	$\bar{x}$	**σX**	R
Loss of profitability	4.41	1.125	1
Break down in cooperation between parties	4.38	1.104	2
Loss of business viability	4.36	0.995	3
Loss of professional reputation	4.33	1.130	4
Loss of productivity	4.25	1.025	5
Cost overruns	4.19	0.938	6
Time delays	4.02	1.138	7
Loss of company reputation	3.98	0.897	8
Rework/ repetition of work	3.96	1.064	9
Additional Expense in administration	3.78	0.989	10
Diminution of respect between parties	3.69	1.093	11
Relocation of Equipment	3.62	1.175	12
Relocation of Material	3.56	1.114	13
Relocation cost of workers/ labors	3.48	1.094	14
Additional Managers cost	3.43	1.058	15

σX = Standard deviation; $\bar{x}$ = Mean item score; R = Rank

9.3. Contributors to construction dispute

Respondent were asked based on their experience as to which factor contribute highly to the occurrence of dispute in construction project. Communication and people were ranked first with (MIS=4,15 & STD=0,82, &0.94 respectively); unrealistic expectations was ranked second with (MIS=3,98 & STD=0,99); management and culture were ranked third with (MIS=3,96 &STD=1,08 &0.98 respectively); tendering pressure was ranked fourth with (MIS=3,87 & STD=1,013); design was ranked fifth with (MIS=3,83 & STD=1,02); economics was ranked sixth with (MIS=3,78 & STD=0,96); law and contract were ranked seventh with (MIS=3,74 & STD=0,97 & 0.93 respectively); workshops was ranked eight with (MIS=3,65 & STD=1,1); Technical and Legal were ranked nine with (MIS=3,48 & STD=1,15 &0.95 respectively); unpredictable events was ranked last with (MIS=3,39 & STD=0,975).

Table 4: contributors to dispute

Contributors to construction disputes	**$\bar{x}$**	**σX**	R
communication	4,15	0,82	1
people	4,15	0,94	1
unrealistic expectations	3,98	0,99	2
management	3,96	1,08	3
culture	3,96	0,98	3
tendering pressure	3,87	1,013	4
design	3,83	1,02	5
economics	3,78	0,96	6
law	3,74	0,97	7
contracts	3,74	0,93	7
workshops	3,65	1,1	8
Technical	3,48	1,15	9
Legal	3,48	0,95	9
unpredictable events	3,39	0,975	10

σX = Standard deviation; $\bar{x}$ = Mean item score; R = Rank

9.4. Strategies to minimize construction disputes

Respondents were asked on the strategies to minimize construction disputes in construction projects in Mpumalanga Province. Most respondents, ranked Stakeholder management and alliancing first with (MIS=3.45; STD=1.151and 1.203 respectively); Lean construction was ranked second with (MIS=3.38; STD=1.058); Partnering was ranked third with (MIS=3.22; STD=1.213); Supply chain management was ranked fourth with (MIS=3.20; STD=0.989) Relational contracting was ranked fifth with (MIS=3.05; STD=1.015); Lastly Alignment with (MIS=2.98; STD=1.249).

Table 5: *Strategies of minimizing construction disputes*

Strategies of minimizing disputes	**$\bar{x}$**	**σX**	R
Stakeholder management	3.45	1.151	1
Alliancing	3.45	1.203	1
Lean construction	3.38	1.058	2
Partnering	3.22	1.213	3
Supply chain management	3.20	0.989	4
Relational contracting	3.05	1.015	5
Alignment	2.98	1.249	6

σX = Standard deviation; $\bar{x}$ = Mean item score; R = Rank

10. Conclusions

Findings from the current study proves that there is a higher incidences of construction dispute in the Mpumalanga region which are caused by poor communication among stakeholders, people, and unrealistic expectation from the client, tendering pressure from the contractors side. The impact of dispute on construction project causes loss of profitability, breakdown in co-operation between parties, the impact on business viability is very bad because companies go bankrupt and shut down, because they cant operate anymore, loss of professional reputation, loss of productivity and cost overruns (delayed payment will occur and project cost will increase with time extension, material increases). To decrease the occurrence of dispute in a project, dispute avoidance strategies have to used such as stakeholders management, alliancing, lean construction, Partnering. Early involvement in the decision making process by the key stakeholders including the clients, contractors and building users is normal the best strategy. Pro-active project environment can be created in which change management is an acceptable tool. Furthermore, to avoid the bad impact the dispute has on projects and the companies risk should be managed and minimised. Therefore, risk must be managed well and also must be transferred to a party that is competent in assessing, analysing and minimize them, hence the early involvement of all the parties is highly recommended. Hence people must be managed well to reduce dispute, because they play a huge part in the productivity and profitability of the project. So People do have an impact to the project as whole.

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The Mind Mapping Technique in Project Management

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Abstract

This article presents the mind mapping technique which, despite many potential benefits, is still infrequently used in project management.

The case study provides practical examples for use of the mind mapping technique when implemented in construction projects.

The results of this study showed that the mind mapping technique helps project managers solve problems, define the scope of a project, schedule packages, and manage teams more effectively. Further, mind maps are useful for creating project plans, and for analysing existing plans so that they are easily understandable.

This study concludes that the mind mapping technique is a creative and useful tool for project managers. The mind mapping technique enables the project manager to gather, manage, share, and communicate information quickly and easily.

Keywords: mind mapping technique, project management, new tools for planning

1. Introduction

Construction projects are characterised by a specific uniqueness, distinctiveness, and complexity. To be successfully implemented, every project needs to be properly managed. In its Project Management Book of Knowledge guide [1], the Project Management Institute lists the following types of competencies that are necessary to manage projects: managing the integrity, scope, schedule, costs, and quality of a project; managing human resources; managing communications within a project; managing risk in a project, managing procurement and stakeholders. Each of these areas requires the use of various tools and techniques that support the process of project management.

The mind mapping technique is one of these tools. However, even though it offers numerous advantages when used in the process of managing a construction project, it is not widely used by construction project managers. This paper presents a case study in which the mind mapping technique was used in managing a construction project in Poland. The paper aims to extend the knowledge of opportunities and practical aspects of the mind mapping technique for construction projects.

The article proposed the name "construction project mapping" in relation to mind mapping regarding project management.

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Construction project mapping of project management knowledge areas and examples of possible tools in each area are shown in Figure 1.

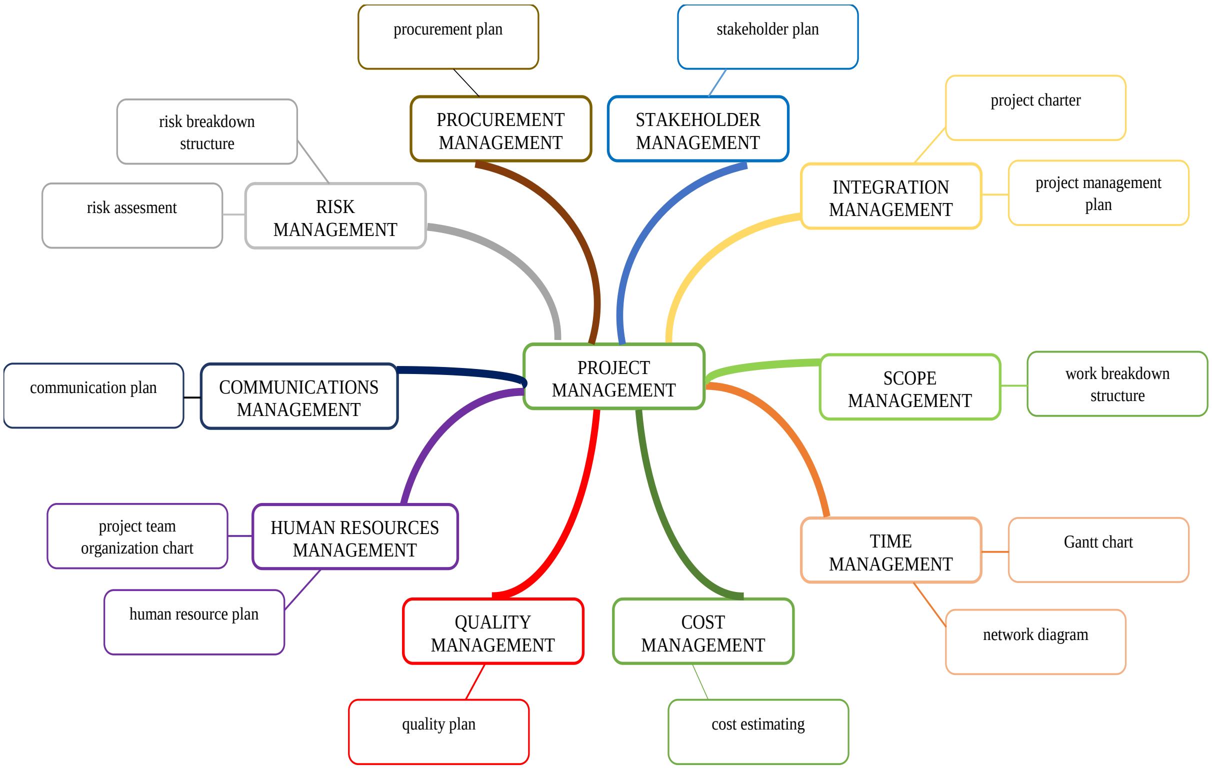

Fig. 1. Construction project mapping of project management knowledge areas and examples of possible tools in each area.

2. The mind mapping technique

Tony Buzan created the mind mapping technique and he is one of the leading international experts in learning techniques and brain functioning. In books [2,3], he describes the basic concepts and premises of mind maps. The characteristic feature of this technique is the use of keywords and images. The main concept or idea is presented in the middle – it often takes the form of an image. From this central image, the most important concepts related to the presented idea branch out. This is the first level of the map. From each of these branches, second-level branches run out – the lines that represent these branches are thinner than the first-level ones; third-level branches stem out from the second-level ones, and these lines are even finer.

The principle of mind mapping creation is shown in Figure 2.

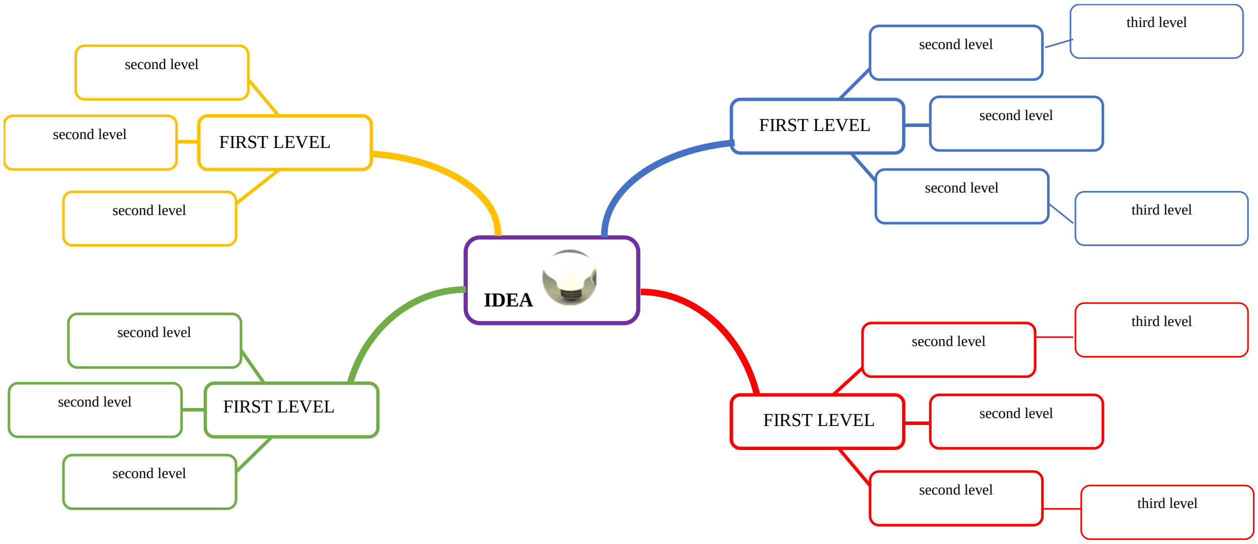

Fig. 2. The principle of mind mapping creation.

There are several possible applications of the mind mapping technique in learning processes [4, 5, 6, 7, 8]. However, few papers discuss the possibility of applying this tool in the context of project management. The paper [9] presents the application of the mind mapping technique in the identification of risk management, which an integral component of project management. This paper extends previous research through a focus on the use of the mind mapping technique in project management.

The paper [10] consider applications for mind mapping in: project management, brainstorming, planning, presentations, interviewing, analysis and problem solving, decision making, meetings.

Mind mapping shown in article [11] were done to emphasise the capabilities of this technique in an iterative way, from the wide concepts of using mind mapping, down to specific examples particularly relevant to patent searching.

3. Case study

In utilizing the mind mapping technique for project management, the case focuses on a building, which is used as a production hall. The site consists of the main production building, a warehouse and a two-storey office/production building. Moreover, there are internal access roads, car parks, and a gatehouse.

The analysed building is made of reinforced concrete and the roof is made of trapeze metal sheets. The external walls are made with autoclaved aerated concrete blocks, which are covered with corrugated metal sheets on the outside. The gatehouse is a one-storey traditionally made (brick) building.

The paper presents the way in which the mind mapping technique was used in selected project management fields, where it's called "construction project mapping".

Firstly, the mind mapping technique was used to prepare SWOT and PEST analysis.

Construction project mapping of SWOT analysis as a strategic planning technique is shown in Figure 3.

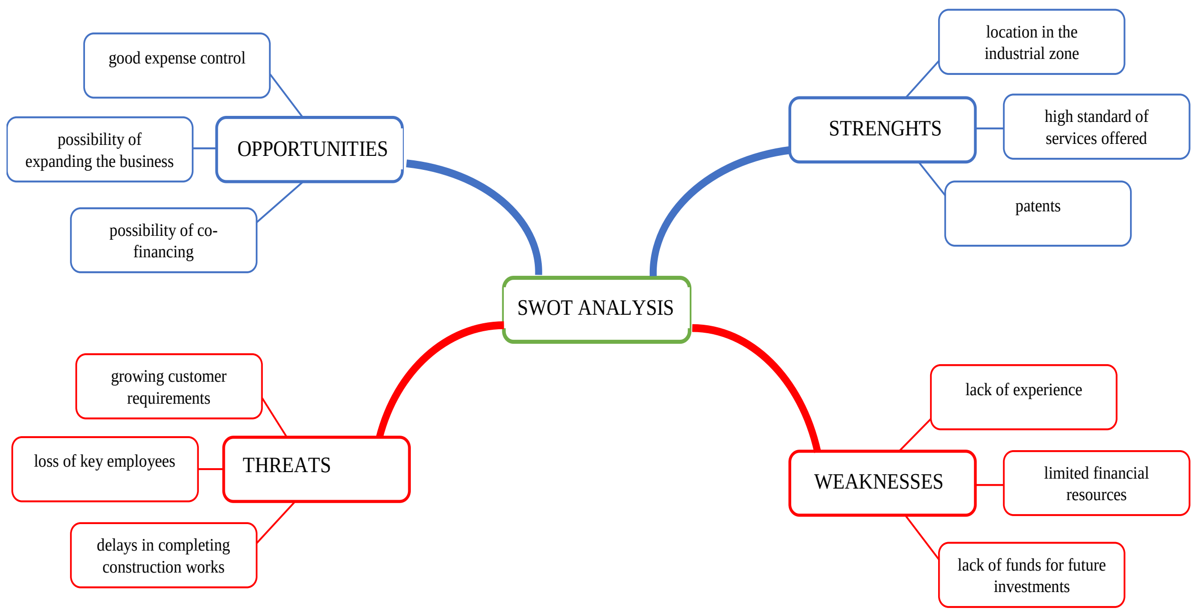

Fig. 3. Construction project mapping of SWOT analysis from the investor's point of view.

Construction project mapping of PEST analysis is shown in Figure 4.

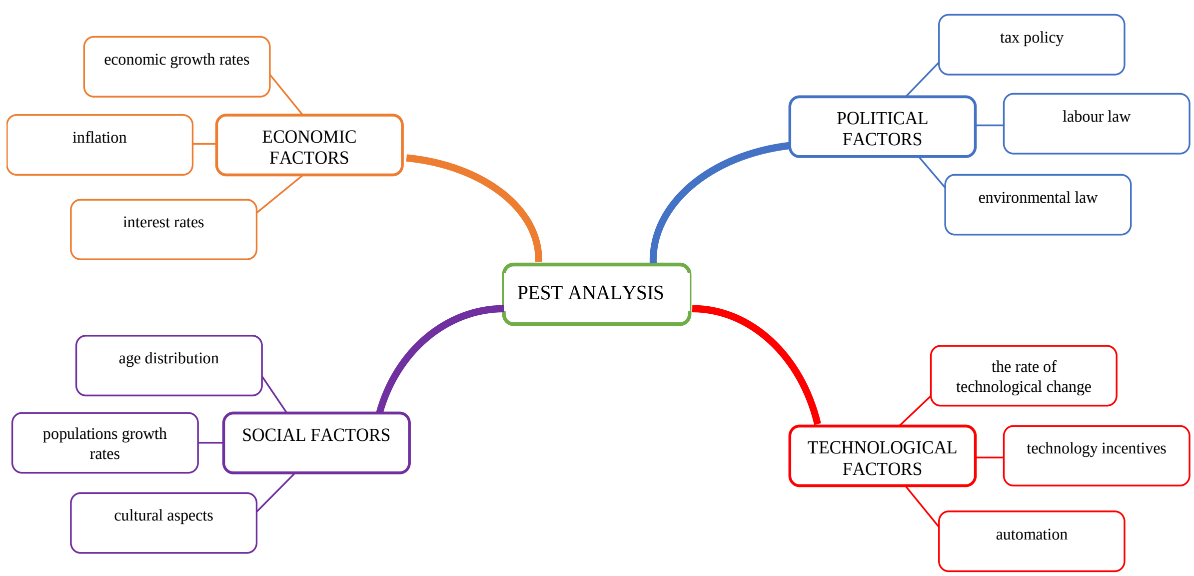

Fig. 4. Construction project mapping of PEST analysis.

Next, the mind mapping technique was utilized to prepare a work breakdown structure (WBS). WBS is based on dividing a project into main tasks, and then dividing these tasks into sub-tasks. This allows personnel to manage the scope of a project in an effective way, and to plan the execution of all the particular tasks. In the case of construction projects, a WBS is usually presented in the form of a chart or a list. In this paper mind mapping was using as a different visualization tool for breakdown structures.

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There are several types of WBS, for example [12]:

- product-oriented WBS (project subdivided according to deliverables or products to be produced),
- function-oriented (process-oriented) WBS (project subdivided according to work function).

Figure 5 illustrates selected product-oriented WBS fragment with cost and resources elements using construction project mapping technique.

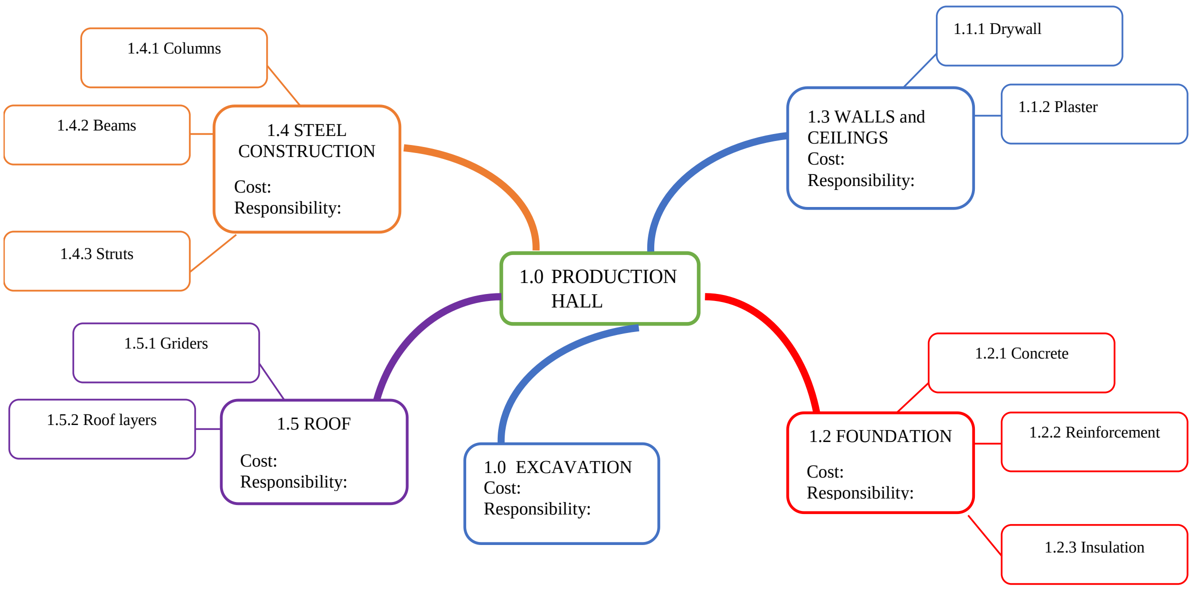

Fig. 5. Construction project mapping of selected product-oriented WBS fragment

Figure 6 illustrates selected function-oriented WBS fragment with cost and resources elements using construction project mapping technique.

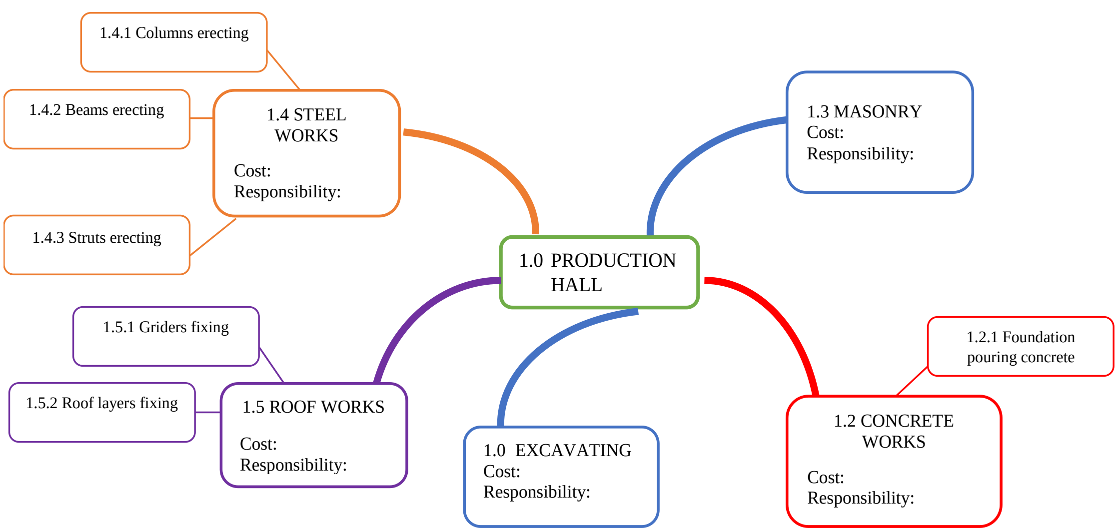

Fig. 6. Construction project mapping of selected function-oriented WBS fragment

Project management has some similar tools to Work Breakdown Structure (WBS) and there are for example:

- Cost Breakdown Structure (CBS) - represents the financial breakdown of a building project into cost targets for work packages.
- Organizational Breakdown Structure (OBS) - represents the resources required to perform the project work packages.
- Risk Breakdown Structure (RBS) - is an hierarchical representation of risks.

Each breakdown structure and its modifications can be presented using the mind mapping technique.

There are several papers on the breakdown structures, such as CBS, OBS and RBS [13, 14, 15], but none of them uses mind mapping technique.

In the next step, the article presents also how mind mapping might be used for stakeholder identify. The article shows the process of stakeholder identification using mind mapping, because it is one of the most important processes in project management and has a potential impact on project success.

Construction project mapping of stakeholder identify is shown in Figure 7.

Fig. 7. Construction project mapping of stakeholder identify.

The article presents examples of mind mapping applications in project management. The mind mapping technique can be used in all areas of project management.

In addition to the mind mapping technique, there are more project management tools are capable to make different breakdowns based on the same database with the use of the sophisticated coding system. However, none of these tools construct information in such transparent way like mind mapping. Mind mapping helps to better analyze, understand, synthesize and generate new ideas.

4. Summary

The paper illustrates how mind mapping techniques can be used in managing a construction project.

Mind maps offer the following advantages:

- they present information in a transparent way, so that information is easy to understand,

- they help personnel in collecting and organising thoughts, arguments and ideas,

- they facilitate time management and help increase productivity,

- they play a significant role in generating new and innovative ideas,

- they are a perfect tool that facilitates strategic thinking,

- they make decision-making easier.

Mind mapping can be recommended as a simple and effective tool supporting the work of the project manager. By non-linear organizing of information, it allows to visualize the natural process of creative thinking and allows to control over the whole complexity of projects.

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The Strategic Application of Building Information Modelling (BIM) to the Role of Construction Project Management

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Abstract

The iron triangle which contains time, cost and quality plays a very important role in the construction industry. Building Information Modelling (BIM) has triggered the way the construction industry operates and in particular 5D BIM. This dimension within the BIM model is more associated with the cost aspect of the iron triangle and the potential to be used by the constructional project manager or built environment professional to streamline workflows and increase the quality of services they provide to clients. 5D BIM encompasses the traditional 3D (three dimensional) model added to the 4D BIM time and then the costing as the fifth dimension. 5D BIM provides the contractor with the ultimate opportunity to produce accurate costs of projects, the expected timeline when the actual costs of the projects will occur, at the same time allowing the schedule to be optimised by taking into account the quantities of material produced from the 5D BIM model and the productivity rate of the project team. The 5D BIM model provides a great platform for the construction project manager to connect the processes of design, construction methods and costs; this on the other side calls for the construction project manager to embrace the digital transformation in the way quantity take off (QTO's) are produced. this research focuses primarily on the role of the construction project manager in south africa whereby bim is been perceived as merely being a software. the research method adopted a quantitative approach and qualitative approach were semi-structured interviews were conducted to get a clear picture of the digital transformation of the construction project manager professional. The findings show that in south africa and in particular the construction project manager still use the old method of using Computer Aided Design (CAD) and 2D models to produce the costs. The research will be important for the construction industry and in particular for the QS practitioner to produce more accurate costs and thus productivity rate.

Peer-review under responsibility of the scientific committee of the Creative Construction Conference 2019.

Keywords: 5D BIM; Building Information Modelling; Computer Aided Design; construction project management

1. Introduction

Building Information Modelling (BIM) with its momentum and capabilities is gaining attention in the Architecture, Engineering and Construction (AEC) industry. The new methodology has made it possible for construction problems to be resolved in association to issues of management of information in comparison to the old processes [31]. [3] states that BIM has the ability to produce quick estimations of cost schedules such as Quantity Take Offs (QTO's). According to [10] cost analysis can be produced at any point, which is defined as five-dimensional BIM (5D BIM) technology. [31] believes that 5D BIM, plays an important role in the integrated project delivery approach. Several

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efforts have been undertaken to investigate the 5D BIM application [37;7; 11] and the role of the Quantity Surveyor's (QS's) [31] within the process of using 5D BIM. However few have researched the challenges of 5D [38; 17] and the role of the QS.

Quantity Take off (QTO) is extremely important in a construction project mainly because of the management application which is applied to infrastructure has to be accurate and consistent. QTO is normally completed manually or even using necessary software's from 2 dimensional (2D) and 3 dimensional (3D) Computer Aided Design (CAD) drawings. The construction industry has accepted the adoption and implementation of BIM and the utilisation of the collaboration tool makes it possible to automate the QTOs process by using 5D BIM QTO tools via model based quantity extraction techniques. However QS's have fears and concerns that the 5D BIM process will eliminate the profession completely. Therefore, this paper wants to explore the approach of 5D BIM among QS's perspective in the South African context, taking in consideration those from both academia and industry.

2. Literature Review

The main problem and the relatively high confusion in the construction industry is related to what BIM is and this is because of the many definitions the methodology has [12, 5, 28, 23] Building Smart continue to be the leaders of BIM implementation and developers over the past several years and they have also investigated the terminology of BIM. Building Smart have defined BIM as;

"A Building Information Model is a 3D object database that can be easily visualised, has rich data and structured information. Building Information Modelling is a process of representing building and infrastructure over its whole life cycle from planning, design, construction, operations, maintenance and recycling. BIM importantly provides a framework for collaboration, a multi-disciplinary environment that brings together all the parties that design, construct and operate a facility, suggesting a new model of procurement Integrated Project Delivery (IPD)" [5].

[28] believe that BIM does not only involve the use of software's however it requires a different manner of thinking and a completely new way of project delivery and procurement. Therefore it becomes a very important for industry professionals to move away from the old ways of delivering projects amongst the different industry role players who are working on separate information typically with the incompatible and different technologies to a totally integrated common platform where professionals can come together to work and share the same information.

BIM is more than 3D modelling and it has other dimensions such as the 4D BIM (time), 5D BIM (Cost) and 6D BIM (Facilities management). The 4D bring the information and data from the 3D model with facilities, scheduling data and project programming and ultimately interprets and does an analysis of the construction activities. 5D brings together all the relevant information with the cost data such as prices, quantities and scheduling. The 6D represent the as-built model which can be utilised during the full operation stages of the building. [19] states that *"the role of the Quantity Surveyor should embrace the 5th dimension and become the key players in the BIM environment - the 5D Quantity Surveyor".*

[21] supports [19] and states that the value of the QS is for the professionals being able to explore and simulate the different construction and design scenarios in real time through having their quantities and cost data linked in the live model.

The concept of Integrated Project Delivery (IPD) is regarded as playing a huge role to a successful adoption and implementation of BIM. According to the American Institute of Architects IPD is defined as *"a project delivery approach that integrates people, systems, business structures and practices into a process that collaboratively harnesses the talents and insights of all participants to optimize project results, increase value to the owner, reduce waste, and maximize efficiency through all phases of design, fabrication, and construction"* [1]

The study by [2] discovered that the implementation and adoption of BIM in collaboration with IPD, the strategies can improve productivity by 6-9%. The [9] study investigated 32 construction firms in the USA which had adopted and implemented BIM and discovered that *"Cost Estimating accuracy fell within 3% range, up to 40% elimination of unbudgeted change, savings of up to 10% of the contract value through clash detections, up to 80% reduction in time to generate cost estimates and up to 7% reduction project time"*.

2.1 The Implementation of BIM

[27] conducted a study of BIM adoption and implementation by the project managers or quantity surveyors in the United States of America and United Kingdom which is almost to be the most comprehensive study of this type to invest the adoption and implementation of BIM across the world into construction thus far. The study provides a picture of the level of BIM adoption and implementation by the built environment profession and the problems which they came across which may be applicable to other countries.

The study was distributed to 8500 RICS members in the year 2011. The study discovered the following;

Only 10% of QS firms used BIM regularly with a further 29% having limited engagement with BIM. Accordingly 61% of QS firms had no engagement with BIM. For the QSs that were using BIM the most frequent use was for construction scheduling (14%) followed by the extraction of quantities and facilities/asset management (both 8%). Only 4% of QS firms regularly invest in BIM training and only 10% actively assessing BIM tools for potential adoption [27].

This indicates that the QS profession in this region is not embracing BIM to the level that is needed. However, given that the UK government mandate for BIM usage was introduced at the time of this survey it would be interesting to see what effect this has had on QS firms since then. The biggest barriers for QS firms adopting BIM were cited as the lack of client demand, training, application interfaces and standards.

2.3 BIM for the QS: 5D BIM application

BIM provides the Information Technology (IT) platform where all AEC disciplines can come together to collaboratively share and ultimately work effectively [6; 25]. This allows for an approach which enables for the easy trickle of data right through the phase of the project, equivalently the better cooperation amongst collaborators allows for easy and quick data move by bringing together the different types of industry professionals within a single model [13]. [32] believes that 5D BIM allows for the project manager to focus their efforts in bestowing their expertise and knowledge to the project team, because through the 5D BIM process is significantly reduced. According to [21]5D BIM increases the usefulness of the QS service by providing the capabilities to envisage, explore and initiate the tremble of different construction scenarios and designs through the blending of quantities, data, project programmes and cost within the model.
Within the BIM model, the integration of the cost aspect is provided by the 5D dimension, which by several consulting organisations, can be seen as an advantage towards cost management [31]. The model gives the project manager the capabilities to measure, take-offs and count straight from a regular updated BIM model through 5D BIM application by connecting the estimating software and the model [14]. According to [4], with the dragging process of qualification in some instances being effortless and automated, this provides more time to the project manager to give for more focus and give the knowledge on other project specification e.g. for instances pricing and factorising risk. Furthermore they has been research conducted which look into 5D BIM and how this dimension helps the role of the project manager [37; 7; 11] the main benefits of 5D BIM is more towards cost estimating and scheduling [30; 34] the potential benefits can be more than schedule and cost estimation. For example "[15] *suggested a way to analyse cash flows through the use of automated processes, which includes QTO scheduling and cost estimating. Additionally, operational and lifecycle costs could also be analysed and appreciated before the building is built using collaborative procedures, which in turn, can lead to cost savings* [17]'.

2.4 BIM for the QS: Challenges of 5D BIM

Design detail:

The accuracy and quality of the model will depend to what extend the construction project has been explained to the QS [18]. Among the concerns experienced by the project manager in the BIM model is the shortage of available data presented within the model. This will arise from the representation (2D or 3D models) which are created by the designer. The Royal Institute of Chartered Surveyors (RICS), has stated that the one of many tasks of project manager is to analyse BIM models for information richness and accuracy, furthermore on several instances it has been stated that the BIM model would not have the needed data to assist with the QTO's and model based measurement [32]. [33] agree with [32] state that the missing information and inadequate details within the BIM model results in inaccurate information and design errors. According to [37] makes the argument that the BIM model that do not have all the information which is required by the project manager to perform precise estimations can lead to problems in searching and managing for the needed data within the model.

Standardisation

Quantities which are generated from the model are in line with the parameters which are positioned by the software vendors who do not go according to the conventional procedure of measurement. According to [29] consistency and accuracy of the information may be at danger because of datasets are transmitted using the different format. According [32], the lack of consistent modeling standards, can lead to the QS having to obey to several approaches, which has a pessimistic impact, resulting in inaccuracies and inconsistencies.

Training and Skills

The full adoption of BIM has been endorsed and mandated by the United Kingdom (UK) government since the year of 2016, whereby all government funded projects must implement level 2 using BIM (2016), however on the upside of this mandate, a survey which was undertaken in the UK made arguments, that this task is unachievable. The findings of the survey revealed that some firms or organisations are not able to fund this process of introducing and incorporating BIM in their organisations because this would require training and educating their workers, which ultimately require cost and time dedication within the organisation. [32] believes that the education of BIM can be helped by universities offering the under-graduates the basic knowledge needed before going to the industry to practice as a professional.

3. Research Methodology

From the available literature it was shown that there has not been any current study which has been conducted on the strategic implementation and adoption of BIM by QSs as part of project manager in South Africa. The Republic of South Africa has six professional bodies in the built environment which fall under the Council for the Built Environment (CBE) mandated by The Department of Public Works, one of the professionals where data was gather from was The South African Council for Quantity Surveyor's Professionals (SACQSP). This research utilised quantitative data collection methods from which rich data was gathered to reveal significant findings. The questions adopted a 5 point likert scale because this is the most popular method amongst researchers and the method is easy to commute with the respondents [16;8]. The questionnaire was comprised of 12 questions which were designed to explore the following aspects; 1) the current adoption of BIM levels amongst the QS's, 2) awareness of 5D BIM and 3) the readiness of 5D BIM adoption. The respondents were categorised to identify whether they are employed by Government, contractors, institutions of higher learning or by quantity surveyor's consultancy firms. The second aspect of the questions related to what BIM was used for clash detections, costing, design or management etc. This was followed up with questions of who requested BIM to be used for the project the contractors, client, management etc. The final aspect of the questions related to software's which are used and the importance of BIM.

4. Findings

This section shows a detailed exploration accomplished through statistical contrast of responses obtained from the questionnaires distributed to the members of the South African Council for Quantity Surveyor's Professionals, who predominantly work as construction project managers.

4.1 *Please indicate your level of experience in the construction industry.*

Figure 2 profiles the respondents in terms of the years they have been active in the construction industry and their experience. The majority of the respondents have only been in the construction industry for less than 5 years at 41% of respondents, followed by those who have been in the construction industry for more than 10 years at 38% and followed up by respondents who have been in the construction industry between 6-10 years at 21%.

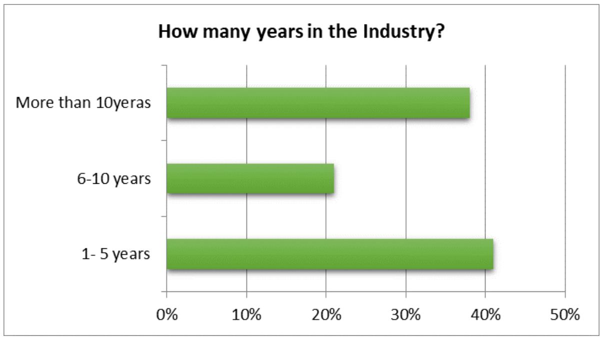


Figure 2: Number of years in the construction industry.

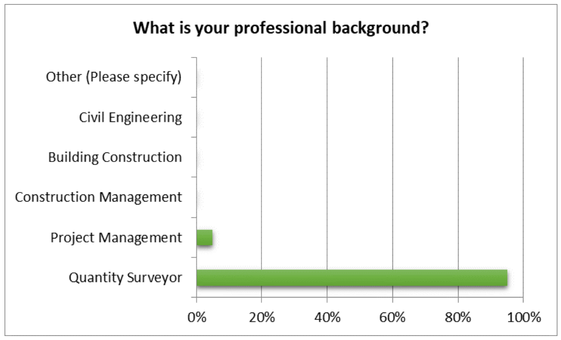


Figure 3: Professional Background

4.2 *What is your professional background?*

Figure 3 depicts the professional background of the respondents from the questionnaire. The majority of the respondents from the questionnaire are Quantity Surveyors at 95% of them which is then followed by some of the Project Managers at 5%. It is not surprising that the majority of the respondents are Quantity Surveyors, because the majority of the respondents came from the Council of Quantity Surveyors, who are already practicing in the industry.

4.3 *What type of organisation do you work for?*

The majority of the respondents were working for the Quantity Surveyors consultancy firms at 49%, which was followed by 27% of respondents working for Contracting firms who are employed as Quantity Surveyors for their employers which was then followed by 12% of respondents employed by Government Departments, followed by State owned entities at 7% and lastly followed by others at 5% which were (1) Institutions of Higher Learning and Professional Organisations.

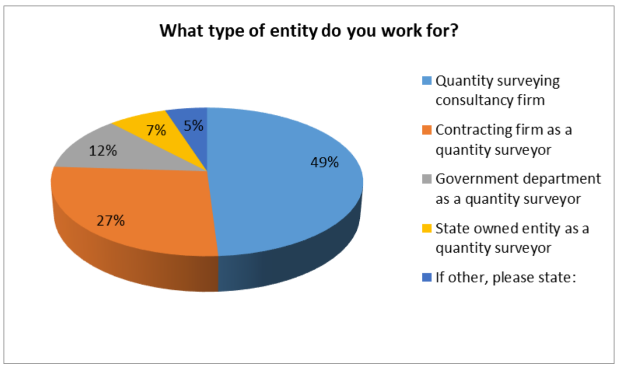


Figure 4: Type of entity

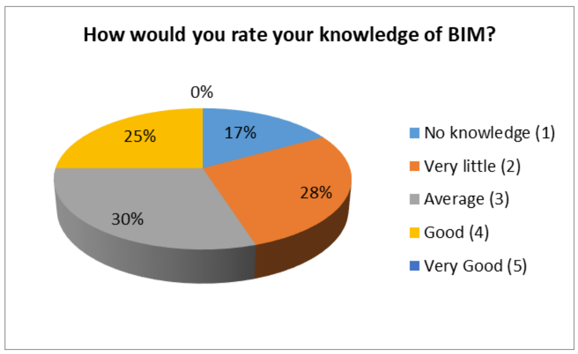


Figure 5: Knowledge of BIM.

4.4 *How would you rate your knowledge of BIM?*

Figure 5 was looking to understand the level of BIM knowledge amongst the Quantity Surveyors. The respondents were asked to rate their level of knowledge about BIM using a 5 point likert scale. The majority of the respondents at 30% rated their level of knowledge of BIM at 30%, which was followed by 28% having very little knowledge of BIM, followed by good knowledge at 25%, then those who had little knowledge were at 17%. It was very interesting that from the respondents that neither of them had very good knowledge of BIM.

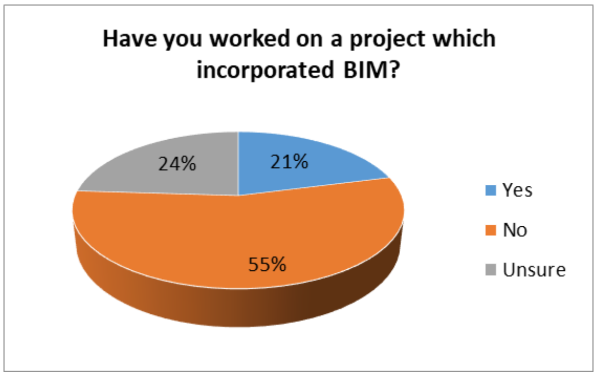


Figure 6: Project which incorporated BIM in the past 3 years.

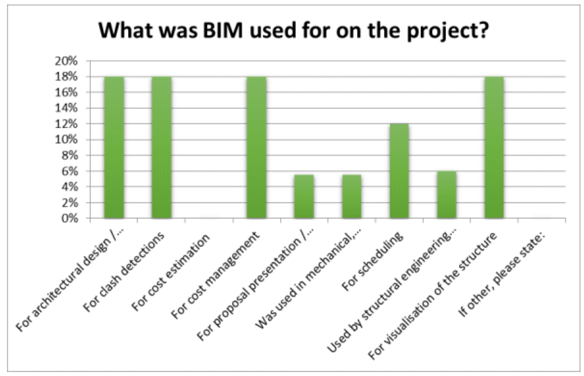


Figure 7: What was BIM used for?

4.5 *Have you ever worked on a project which incorporated BIM in the past 3 years?*

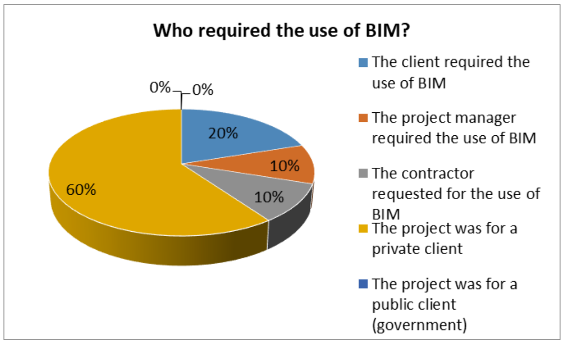
The authors had to probe the project which had incorporated BIM in the past 3 years. The results show that 55% of the respondents had not worked on a BIM project in the past 3years, while 24% of the respondents were unsure if they had worked on a project which had incorporated BIM in the past 3 years and 21% of the respondents had worked on project which incorporated BIM in the past 3 years.

4.5.1 If the answer to above is "yes", what was BIM used for?

When the respondents were quizzed about what BIM was used for on the, the responses were interesting. Architectural design/ modelling were ranked at 18% from the respondents, followed by it was used for clash detections at 18% also, interestingly enough neither of the respondents indicated that BIM was used for cost estimating. Cost management came in at also 18%, while 6% used BIM for proposal presentation and marketing, while 6% used BIM for mechanical, electrical and plumbing (MEP) design, 12% used BIM in their projects for structural engineering design and 18% used BIM for visualisation of the structure.

4.6 *Who required the use of BIM on the project?*

This was a critical question which the authors had to interrogate, being fully aware that when looking at available literature that some North America, Europe, Scandinavian region and Asia BIM is entirely endorsed by Government. 60% of the respondents stated that the use of BIM was required by private clients, while 20% was required by a client, while also some project managers also required BIM to be used at 10% and the contractor also requiring the use of BIM at 10%. What was interesting was that Government and States owned entities did not require any BIM to be used on public funded projects. This is clear shows that the South African Government is still far behind in the implementation and adoption of BIM on publicly funded projects. One of the project value of the project which was required to use BIM was valued at R11 500 000.



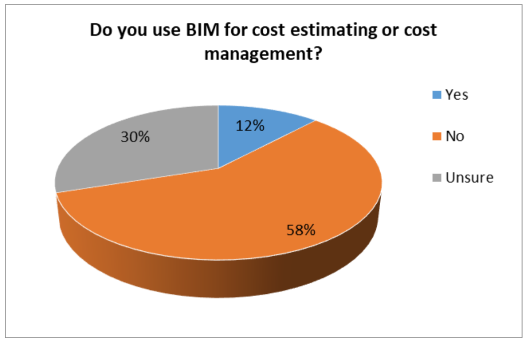


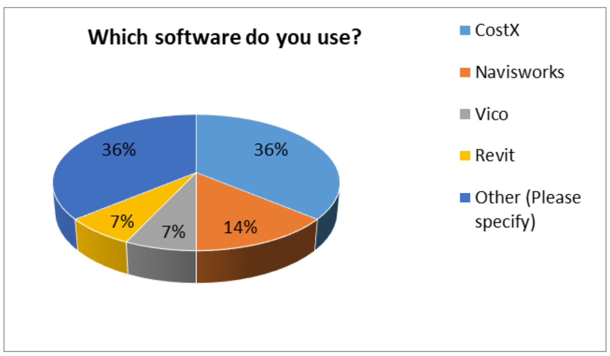
Figure 8: Who required the use of BIM on the project. Figure 9: Do you use BIM for Costing?

4.7 *In your organisation do you use BIM either for quantification, cost estimating, cash flow or cost management?*

For the authors to fully understand the level of adoption and implementation amongst the Quantity surveyors, they had to probe this question rigorously. A large majority at 58% have not used BIM either quantification, cost estimating, cash flows or for even cost management. While 30% of the respondents were not sure if BIM was used for cost estimating, quantification, cash flows or cost management. Only a small margin of 12% have used BIM for either quantification, cost estimating, cash flow or cost management.

4.7.1 *If the answer to above is "Yes" Which software was used?*

It was critical for the authors to find out which software's were used in their organisations. The most popular software at 36% was CostX used in respondents organisations, which was then followed by Navisworks at 14% then also Vico at 7%. The Revit software was at 7% used by respondents which was followed by other at 36%. The "other" software in this instance being WinQS. What the authors also wanted to find out was how long were these software's were used in their respective organisations. The number of years ranged from 1 year and 6 years of using these software's.



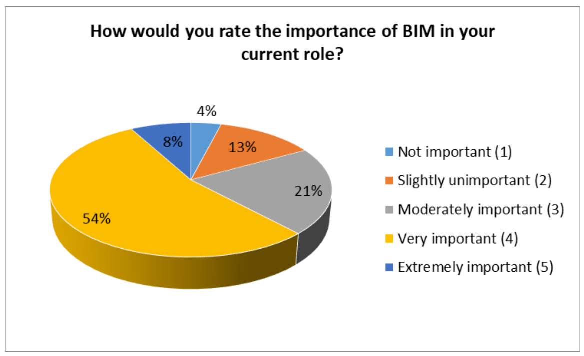


Figure 10: Software used

Figure 11: The importance of BIM

4.8 *How would you rate the importance of BIM in your current role?*

Figure 11 was looking to understand the level of importance amongst the Quantity Surveyors. The respondents were asked to rate their level of knowledge about BIM using a 5 point likert scale. The majority of the respondents at 54% believed that BIM was very important, 21% stated that BIM was moderately important, while 13% believed that slightly important, 4% of the respondents believed that BIM was not important and 8% stated that BIM was very important for them. One of the comments by a respondent was that *"Unknown as I have not used it"*.

4.9 *How would you describe your organisations future use of BIM?*

What was evidently clear was that the level of BIM implementation and adoption amongst the Quantity Surveyors was not strong enough. In future looks like the implementation and development of BIM will be on rise in South Africa among the QS's. The majority at 50% of the respondents replied that they will be fully using BIM in their Projects in the next coming 3 years. While a significant 30% state that they will be incorporating BIM in their respective organisations in the next 1 year and 20% of the respondents say that they will only begin to use BIM in their organisations in the next 5 years. One comments from a responded was that *"I don't think we will use BIM as currently there is no understanding what it is and its benefits for State Owned Entities (SOE's) and Government".*

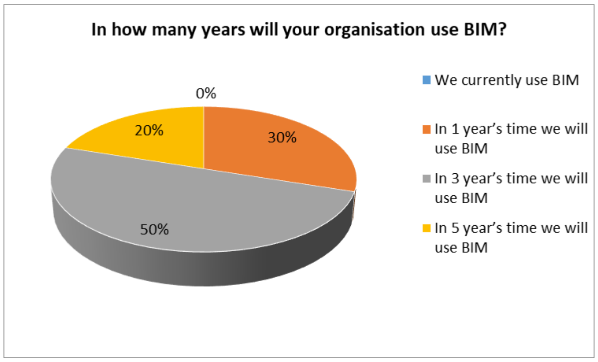


Figure 12: Years organisation will use BIM.

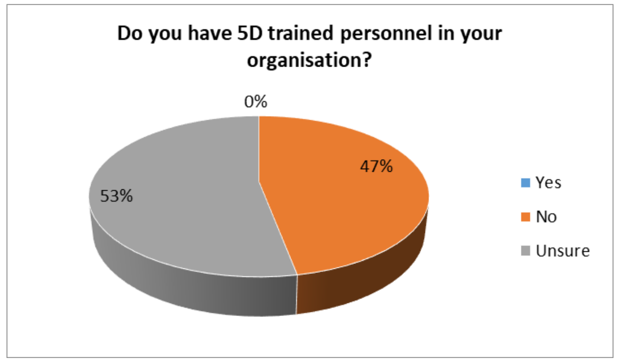


Figure 13: Trained personnel on 5D BIM

4.10 *Do you have 5D trained personnel in your organisation?*

With this question the authors wanted to find out if in the respondents organisations they had any sort of training in 5D BIM. It was clear that this has not been done in either of the respondents. 53% of the respondents were not sure if they had any personnel who was trained in 5D BIM and while 47% of the respondents stated that they had not personnel within their organisation who had training on 5D BIM.

5. Discussions of findings

This study in particular explored the application of and adoption of Building Information Modelling by the South African Quantity Surveyors operating in the construction industry. A study of this kind has not been undertaken in the South African context, however when looking at available literature similar studies have been conducted in other countries. The study by Mohammad, Michael, and Sharon, [20] which conducted in the United Kingdom investigated the integration of a QS's role and practice within the BIM process to enable better implementation of 5D BIM. Furthermore the study by Patil and Manish [24] focused on BIM application for Project Scheduling and Costing of Construction projects including barriers in implementing BIM. Also the study by Olatunji, Sher and Gu [22] explored the relationship between BIM systems and the roles of quantity surveyors in the construction industry. This study focused on BIM as it relates to the built environment in South Africa.

BIM is implemented in the South African built environment Profession. However it's still not extensively adopted. There are several challenges for implementing BIM as well as using BIM based QTO. Shifting from CAD based current South African construction industry to BIM based system need a lot of requirements like hardware, software and livewire alterations. Hardware includes system requirements to implement BIM and software includes the BIM platforms and other BIM tools and livewire includes construction industry professionals who need to have knowledge on BIM tools in their respective practices. Still after implementing, interoperability and IFC supported BIM platform and BIM tools selection will only lead to successful quantity extraction. Except the challenges in implementing BIM, with in BIM based QTO, competency of professionals is an ultimate requirement for success.

6. Conclusions and Recommendations

This final section the author will provide the conclusions and recommendations based on the data gathered from the different respondents by way of questionnaires. It becomes very important and critical that the conclusions be taken to heart and consideration by the project manager if they are to be able to participate in the 4IR and not get left behind.

Recommendation 1:

What was critical and clear was that there was not enough level of knowledge about what exactly BIM is among the Quantity Surveyors particularly 5D BIM. It is recommended that the professional council of Quantity Surveyors have seminars which are compulsory to attend, most importantly BIM should be taught in undergraduate studies in the universities as this is where the foundation is build before going to become a professional. That way when an individual enters the professional world or industry they are already knowledgeable about BIM.

Recommendation 2:

Quantity Surveyors need to start using 5D BIM for quantification, cost estimating and cash flows or cost management and how this can be done is individuals should be provided training sessions whereby Continuous Professional Development (CPD) points are awarded to individuals. Training can be provided by Universities who have capabilities or training facilities and trained staff in BIM specifically on 5D BIM.

Recommendation 3:

What was clear was that respondents acknowledged that BIM is very important, how what will drive the implementation and adoption of BIM amongst these Quantity Surveyors is cultural change for than anything else, Especially the mindset need to change and start thing about how 5D BIM will help them out in doing their job and not be afraid of change and technology.

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The transportation management framework for the Polokwane Local Municipality during the Zion Christian Church Easter weekend pilgrimage

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Abstract

The high volume of traffic to the Holy City of Moria during the Easter weekend could be graphically described as taxing to both the motorists and pilgrims. The rationale for the study was to understand, investigate, analyse and describe the role of the Polokwane Local Municipality (PLM) in the planning and the execution of the Zion Christian Church (ZCC) Easter weekend pilgrimage with a view to reducing vehicular traffic. The PLM is home to the Zion Christian Church (ZCC), that hosts one of the biggest mass gathering event on the African continent, but researchers and the media have paid little or no attention to this pilgrimage which attracts more than 15 million pilgrims during the Easter weekend. It is notable that a mass gathering is an event attended by enough people to strain the planning and response resources of a community, state or nation. The researchers adopted an action research strategy with the view to carving out a lasting solution to the management of the high volume of vehicular traffic during the Easter weekend pilgrimage. Judgemental or purposive sampling was chosen over other available sampling methods due to the few experienced municipality employees who work closely with the church in the planning of the pilgrimage. Eight themes emerged during the interaction between the researchers and the municipality. The study graphically showed that there was a lack of synergy between the ZCC and the municipality in the execution of the pilgrimage. The research findings suggested that; traffic congestion was attributable to a vehicular-centric approach to transport planning in South Africa. The heavy reliance on vehicular transportation by South Africans is a cause of road accidents. The study recommended an introduction of a pilgrim train for the church with a view to reducing vehicular traffic congestion during the Easter weekend pilgrimage for the collective good of both the motorists and the pilgrims.

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Keywords: Cooperation, Execution, Infrastructure, Planning, Services and Stakeholders.

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INTRODUCTION

The ZCC's headquarters are at the Zion City Moria, about 25 kilometers east of Polokwane previously known as Pietersburg in the South African Limpopo Province (not to be confused with the underground city, mines and connected tunnels that run through the Misty Mountains in Tolkien's Lord of the Rings). The Polokwane Local Municipality (PLM) and the Zion Christian Church (ZCC) host one of the biggest mass gathering event on the African continent, but researchers and the media have paid little or no attention to this pilgrimage which attracts over 15 million pilgrims during Easter weekend. The number of pilgrims is more than the combined inhabitants of Botswana, Lesotho and Eswatini. Polokwane is a northern Sesotho word that means 'place of safety', but researchers have only focused on the Hajj and the Kumbh Mela as the two-major MG events in the world. Once a year, 3.0 million Muslims from all over the world gather in Mecca to perform the Fifth Pillar of Islam, the Hajj and over 120 million pilgrims attend the Kumbh Mela in India. The Hajj and the Kumbh Mela mass gathering events have received negative media attention due to pilgrims who die on their spiritual journey [1]. For example, in 2015 at least 87 pilgrims died and 184 got injured in Mecca during the Hajj when a construction crane crashed into a mosque. Within a few days, 719 pilgrims died and 800 got injured in a stampede [2].

The Kumbh Mela is replete with several incidents, for example, there has been a fire before the start of Kumbh Mela 2019 in Allahabad, but no one was injured [3]. Another Kumbh Mela devastating event occurred shortly after India gained her independence from Great Britain in 1954, about 1000 people and scores of others were injured whilst the Kumbh Mela in Allahabad was in progress [4]. On the other hand, the Zion Christian Church (ZCC) stands out for its better track record on the safety and the management of the pilgrimage. It is notable that since the church's inception in 1910 hitherto; there has never been a stampede during the pilgrimage, this is thanks to several factors, unalloyed loyalty of the congregants to the faith, the reverential respect which the church members accord their spiritual leader as well as the guardian of the faith and the church values that have been codified into the philosophy of operation. The ZCC pilgrimage receives little academic attention in academic discourse regardless of millions of pilgrims who throng at Zion City Moria (ZCM) in Limpopo every Easter weekend to fulfil their spiritual needs. Historically, the ZCC has been the scoff of society, the Apartheid government and the scientific world. Currently the ZCC is a force to be reckoned with. This muddle-headedness has played down the spiritual importance of the ZCC pilgrimage to its members. The evolution of the ZCC is succinctly captured by the 19th Century philosopher Arthur Schopenhauer who observed that all truth passes through three stages, the ZCC is no exception. First, it is ridiculed. Second it opposed. Third it is accepted as being self-evident [5]. The famous Hebrew poet; King David writes in Psalm 118:22: "The stone which the builders rejected; has become a chief corner stone." [6]. The ZCC has become a chief cornerstone on the African continent and it is currently spreading its wings to other continents.

There is still a big penumbra in literature as to what characterises or constitutes a mass gathering. Researchers oscillate between 1000 and 25 000 attendees [7]. The World Health Organisation (WHO) [8] defines a mass gathering as "An organised or unplanned event where the number of people attending is sufficient to strain the planning and resources of the community, state or nation on hosting the event." The ZCC pilgrimage has all the tenants of a mass gathering event according to the WHO definition. First, the event is well planned, as a result, the church uses tried and a tested strategies and tactics to ensure the smooth running of the pilgrimage. Second, the event increases the high volume of traffic on the road which compels the state to deploy more resources such as health workers, emergency workers, traffic and security enforcement officers. Lastly, the event takes place in the province of Limpopo where there is high volume of traffic due to motorist who travel beyond ZCM to their homes in Limpopo as well as other neighbouring countries. The municipality is expected to create a 'temporary city' for pilgrims and to ensure the smooth running of traffic for other motorists. The pilgrims who visit ZCM increase exponentially from year to year basis. For example, during the 2016 Easter Weekend; 12 million pilgrims were hosted at ZCM and during the Easter weekend of 2017, the number of pilgrims increased to 13 million [9]. There is a great likelihood that several pilgrims are likely to reach 16 million in 2019. The buses, mini buses and the private cars are solicitously parked in the Holy City of Moria by the volunteers under the supervision of the church management. After the pilgrimage, the traffic is ushered out of

Moria in a systematic way without the church members gate tailing one another. The culture of obedience is paramount amongst the ZCC membership. The following figure is an aerial photo of Moria during the Easter weekend pilgrimage.

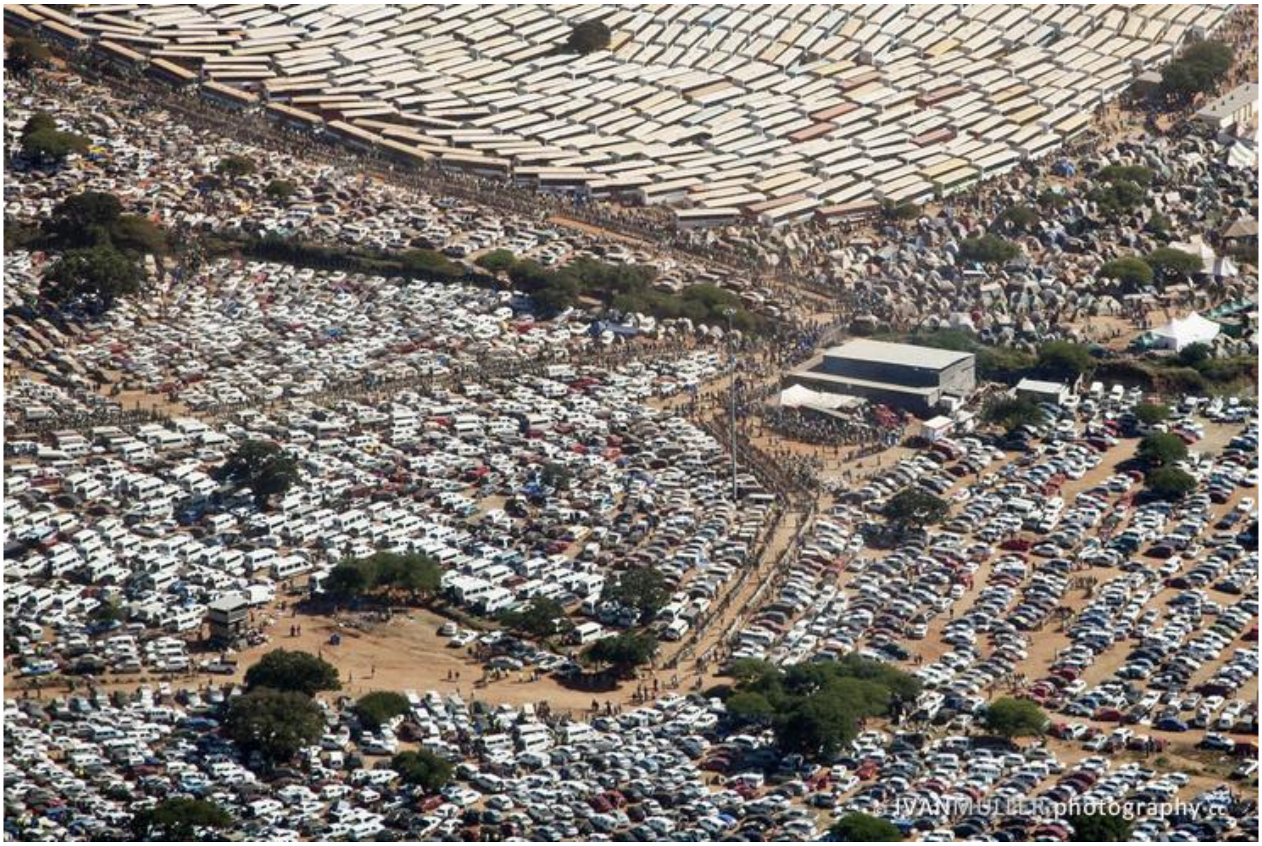

Figure 1: Aerial photo of Moria (photo courtesy of Ivan Muller)

THE OBJECTIVES OF THE STUDY

The objectives of the study are to identify interventions that will contribute to:

- the designing of a structural framework to manage the pilgrimage during the Easter weekend;
- the carving out of strategies to reduce vehicular traffic congestion during the pilgrimage;
- the engagement of all stakeholders in the planning and execution of the pilgrimage;
- the establishment of how communities around ZCM are affected by vehicular traffic during the pilgrimage;
- the creation of an intermodal transport system during the pilgrimage; and
- creation of awareness of international protocols governing mass gathering events.

PROBLEM STATEMENT

Although a pilgrimage is an individual's spiritual journey in search of meaning; it ends up as a collective effort on several stakeholders. Hajj, 22:27 states: "And proclaim the Pilgrimage among men; they will come to you on foot and (mounted) on every kind of camel, lean because of journeys through deep and distant mountain highways" (Quran 22:27-30) [10]. Shariati [11] observes that a pilgrimage without people is no pilgrimage at all. The majority of the ZCC use vehicular transport to reach ZCM. The number of pilgrims who visit the Holy City of Moria during the Easter weekend has increases logarithmically since the founding of the church in 1910. During the 2017 Easter weekend pilgrimage, the ZCC hosted an estimate of 13 million pilgrims. The Hajj organisers on the other hand, know in advance the number of pilgrims who would be attending the pilgrimage in Mecca. Both the ZCC pilgrimage and the Kumbh Mela festival which is considered as the "biggest mass gathering on Earth" plan and execute their pilgrimages without a quota management system [12].

According to WHO [13], the organisers of mass gathering events are required to furnish information about how many people will attend a mass gathering event and who they are likely to be. The ZCC will find it increasingly difficult to apply a quota system since it would sound unAfrican to turn visitors away from a place of worship or your home. Africa is laden with such rich heritage or spirituality and cultural diversity, with abounding hospitality and acceptance. The exact number of pilgrims who attend the ZCC Easter weekend pilgrimage would only be known once the pilgrims reach ZCM. Although African hospitality is paved with good intention, it is not beyond critical appraisal. This African approach makes it increasingly difficult for the local government to anticipate the extent to which services must be provided. Simply put, the relationship between the ZCC and the local government should be asymmetrical in the planning and execution of the pilgrimage. The majority of ZCC pilgrims use vehicular transport to reach their ZCM during the Easter weekend and there is no strategy in place to deal with the transit safety of pilgrims at the local municipality level. For instance, traffic congestion causes bottlenecks which makes it increasingly difficult for ambulances, fire extinguishers and police vehicle to move seamlessly during an emergency.

The ZCC Easter pilgrimage creates a huge challenge for both the church and the municipality in creating a temporary city in which millions of people can stay for a period without, injuries, sickness, stampedes, violence and crimes. In addition, the hosting city should ensure that services like transportation, security, water, electricity and sanitation to make the lives of temporary citizens better. The cooperative partnership between the state and mass gathering event organisers is of paramount importance in the management of public health issues. It is inevitable that mass gathering events come at both financial and opportunity costs to the state [14]. Given that the state must ensure the provision of infrastructure and services during mass gathering; the relationship between the organisers and the state should be symmetrical.

The ZCM annually accommodates millions of pilgrims from all the provinces of South Africa, Southern African neighbouring countries and abroad as a result the local municipal system is temporarily disrupted by the number of pilgrims who throng to ZCM. Briefly put, the number of pilgrims outnumbers the permanent residents of Polokwane and thus putting more pressure on the local economy to deliver services such as, traffic management, security management, water supply, drainage services, medical care, law and order with limited or outstretched resources. It is notable that the consumption of these services by pilgrims far outweighs the existing local supply. Put another way, the demand exceeds the supply. Religious mass gathering events expose the pilgrims to numerous health, safety and environmental hazards, such road accidents, the transmission of infectious diseases, physical injuries and impact negatively on local and global health system and services. The role enacted by the state has some shades of grey in the planning and execution of ZCC mass gathering. The state, as the highest societal organisation is, therefore, playing a secondary or reactive role in the planning and execution of this mass gathering event. Often in South Africa, faith-based organisations enact a primary or a proactive role in the planning and execution of mass gathering and delegating all the consequences to the state. Pilgrimage related costs or externalities are automatically internalised by the state long and transferred to the tax payers long after the pilgrimage is over. The volume of traffic during the pilgrimage makes the mobility of the local community difficult since there is no infrastructure that has been designed for the needs of the pedestrians. Put another way, the infrastructure was only designed for the vehicles and nothing was designed for the pedestrians, ignoring the fact that in Africa and in some Oriental countries such as India, walking is a mode of transport for many people.

The ZCC has also experienced a spate of road accidents. In 2011, eleven people died when the bus they were travelling plunged 40 meters down an embankment on the George's Valley Road outside Tzaneen after the driver lost control [15]). Ten people died and 45 were injured when a bus lost control on the NI highway in Polokwane, after the pilgrims attended a church service in Zimbabwe [16]. In 2016, ten members of the ZCC died in a bus crash at George's Valley Road outside Haenesburg near Tzaneen on a Sunday afternoon. The driver lost control of the bus [17].

According to the 2013 International Transport Forum on Road Safety Annual Report, South Africa performed badly in terms of road safety. The report indicated that there were 28 fatalities per 100 000 population, which was among the highest rates worldwide in 2011. The economic cost of South Africa's road vehicle accidents is estimated to be R307 billion each year [18].

LITERATURE SURVEY

The ZCC is growing its membership beyond the African continent; currently there is a branch in England, Saudi Arabia and another one in Canada. Peters [19] notes that in the nineteenth century, many pilgrims who journeyed to Mecca were indigent or enfeebled by age, or the long journey. The health dangers of collecting large crowds of such people in close quarters and often under unsanitary conditions was not regarded as a serious issue, until an epidemic disease appeared in Hijaz in 1865, in the form of cholera. By the time the Hajj was over, 15 000 of the estimated pilgrims had died of cholera. In 1893 nearly 33 000 pilgrims out of some 200 000 died. Dr Oslchanictzki, who was a physician at the time had this to say in an unpublished memoir:

> "I was sent from Quamaran to Jidda with a colleague to supervise the return of the pilgrims. All was quiet in the city, but we knew that at Mecca there was a veritable hecatomb of pilgrims; more than a thousand were being reported dead daily. An initial convoy of 5 000 camels brought 15 000 to Jidda. The ill had to be kept outside the city and only the healthy were admitted."

On 7 February 1894, the ninth International Sanitary Conference was held in Paris to address the Health and Safety of the Mecca pilgrimage. Sixteen countries participated in the conference, including the USA. Western countries who had colonial interests in the oriental world also attended the conference. The conference was exclusively concerned with the Mecca pilgrimage, and specifically the precautions to be taken at ports of departure, the sanitary surveillance of pilgrims traversing the Red Sea, and the sanitary regulations of shipping in the Persian Gulf. The previous International Sanitary Conferences since 1851 insisted on the need not only for sanitary surveillance of the Red Sea and the Persian Gulf, but also for adequate precautions to be applied to pilgrims' ships at their ports of departure [20]. According to Hammoudi (2006) [21], elevators are a major hazard or death trap for the Mecca pilgrims. Pilgrims overload the elevators beyond their capacity. Crowding and shoving lead to overload and when the cable give way, on the fourth or fifth floor, the elevator crashed to the ground and many lives were lost. On the other hand, pilgrims who travel on buses engage in unsafe behaviour. The buses are packed beyond capacity, with pilgrims on the roof, hanging off the steps and rear fenders.

The Constitution of the Republic of South Africa states that the local government is obliged to serve the local community devotedly and concernedly. The following objects of the local government are well articulated in the Constitution of the Republic of South Africa (Act 108 of 1996) [22]:

- to provide democratic and accountable government for local communities;
- to ensure the provision of services to communities in a sustained manner;
- to promote social and economic development;
- to promote a safe and healthy environment; and
- To encourage the involvement of community organisations in the matters of local government.

The Constitution further states that municipalities must (a) structure and manage its administration and budgeting and planning processes to give priority to the basic needs of the community and to promote the social and economic development of the community; and (b) participate in national and provincial development programmes. Sixolo [23] in his M.A dissertation argues that given the background of separate development in South Africa, the prerequisite for municipalities in South Africa is developmental since the country strives to be a developmental state after years of apartness. A developmental municipality will require social cohesion and technical competence. He opines that developmental municipalities will be compelled to consult with their communities in key policy and decision-making initiatives. Briefly put, developmental municipalities require active citizenship. Suliman [24] defines active citizenship as playing a proactive role in your roles and responsibilities towards your society and environment because you are a stakeholder. He argues that making people realise their role as stakeholders in a democratic state is the first step towards active citizenship.

Service delivery protests are commonplace in South Africa. Vatala [25] describes municipalities in South Africa as agencies for service delivery, economic development, tourism, infrastructure development, safety and security, job creation, poverty eradication and environment sustainability. This was enhanced by authors who opine that the role of the local government is to serve the local community [26]. For the local government to enact its role to deliver services to the community, transformation should take place. According to Van Wyk [27], the democratic local government should turn from public administration into a tool for development. The White Paper on Local Government [28] was promulgated as a tool that brings the local government to the people. The White Paper defines local government as a sphere of government that is close to the people, responsible for infrastructure and services that are essential to the wellbeing of the people. It is notable that the services that are provided by the local government to the local community should be the services that the private sector is either unwilling or unable to provide because the services may be delivered on a non-profit or break-even basis [29]. The Municipal System Act (Act 32 of 2000) [30] section 73 (1) zeroes – in on the fact that a municipality must prioritise the basic needs of the community, promote their development and ensure that communities have access to basic services. Reddy [31] argues that local government must embark on programmes that seek to rehabilitate collapsed infrastructure, systems with the view to providing basic services to the community. Caraley [32] argues that the local government is a pivot on which community live rotates, it causes things to happen which may not otherwise happen. On the other hand, local government plays a preventative role, prevent things from happening which may otherwise happen.

RESEARCH STRATEGY: ACTION RESEARCH

This study was designed in a qualitative dimension. There researchers adopted action research as his strategy. Action research was developed by Kurt Lewin in 1946 [33]. After the researchers have identified their research paradigm as well as the research approach, the next step of the research design is to identify the appropriate research strategy that will lead the researchers to time horizons as well as the data collection process. Saunders [34] identified the following six research strategies namely, experiment, survey, case study, grounded theory, and ethnography and action research. The researchers decided to employ an action research strategy to the study since the researchers could not impose the solution to the organisation under study, but to come up with a collaborative solution. Nieuwenhuis [35] enhances the justification for the action research strategy:

"Definition of action research draw attention to its collaborative or participative dimension and to the focus on a practical problem experienced by participants for which a practical solution is sought. To successfully undertake action research therefore requires an understanding of the context as well as of possible solutions to the problem. Evaluation or assessment of the effectiveness or success of the intervention becomes an important focus in the research. What makes action research a qualitative research type is the strong focus on understanding the problem and developing an intervention with the people involved – it deals with the "why" and the "how" questions."

The aims of action research are better explained by two verbs i.e. action and research, the action component is to bring about radical change in some community or organisation and the research part seeks to increase understanding on the part of the researcher and/or the community or organisation. Dick [36] argues that there are action research methods where the focal point is on action, with research as dividends or a fringe benefit. This study is more on the action rather than on research since its aim of the study is to bring about change in some community or organisation or program. Responsiveness and rigour are the virtues of action research [36]. Reason [37] states the aim of action research is to develop practical solutions in a collaborative manner. There is a difference between the traditional research approaches and the action research approach.

The high volume of vehicular traffic to ZCM during the Easter weekend is a challenge to motorists, pilgrims, communities and the three spheres of government. The researchers used the seven-step model proposed by Van Tonder and Dietrichsen [38]. The justification of the model is that it is aligned with the action research model of Organisational Development (OD). It requires that a diagnosis process should be collaborative and participative towards offering solutions to organisational challenges as opposed to imposing a unilateral theoretical generated solution. This model also fits the ontological stance of the researchers which assumes that reality is co-constructed through engagement with other stakeholders.

The researchers purposively or judgmentally selected people who were knowledgeable about the issue under study [39]. Houser [40] opines that convenience sampling has an added benefit over probability samples pertaining to logistics and cost. The following were the key inputs: semi-structured interviews was used to interview the senior management representatives whose responsibilities included the joint planning and the execution of the ZCC pilgrimage, the services and the infrastructure that are provided by the municipality for the smooth running of the pilgrimage were discussed with the senior municipality representative. The PLM also discussed their disaster management plans, traffic flow plans as well as transport planning with the researcher. The rapport building elements are vital in establishing the relationship of trust and credibility during this phase.

The goal of the first phase was to deconstruct and contextualise the ZCC Easter weekend pilgrimage and the level of participation in the pilgrimage by the PLM. The following outputs emerged from this phase: a detailed account of how PLM participants in the ZCC Easter weekend pilgrimage in both ZCC churches, evidence of traffic and disaster management plans, Integrated Development Plan (IDP) as well as the PLM organisational structure with the view to assessing the capacity of the municipality to deliver the biggest pilgrimage on the African continent.

THEMES EMANATING FROM THE ACTION RESEARCH PROCESS

The following themes were identified throughout the research process:

- Linking transport planning to traffic congestion;
- Pedestrian safety;
- Disaster management;
- Public-private partnership;
- Community involvement;
- Municipal infrastructure and services;
- The use of technology for the pilgrimage;
- Strong church values.

CONCLUSIONS

The ZCC pilgrimage is the biggest pilgrimage on the African continent. It is notable the church was established in 1910 before the establishment of the PLM when African Independent Churches were looked down upon by the government; as a result, the church developed internal processes to deal with the pilgrimage. The role of the municipality in the planning and the execution of the pilgrimage is secondary in that the church has tried and testes systems in place to manage the pilgrimage. Briefly put, the church employs methods that have worked over the year, but there is always room for improvement. It is also notable that since the establishment of the church in 1910 there has never been a stampede as opposed to other religious gatherings such as the Hajj and the Kumbh Mela. The municipality is incapable of enacting a spiritual role to the community, but they can provide services and infrastructure for the collective good of the community.

It is notable that an African pilgrimage is different from other pilgrimages. For example, a strategy such as the quota system which has been a winning strategy for Hajj to manage the crowds would not succeeds in the context of an African pilgrimage. Africa is synonymous with hospitality; it would be unAfrican to turn people away who intend to pay you a visit based on a quota system. Bishop Barnabas Lekganyane [41]; the spiritual head of the ZCC are worth recalling: “The factor which makes the ZCC the largest spiritual home on the continent is its long-standing understanding of the African culture and social fabric. The church seeks to promote good aspects of African culture while preaching and enhancing the Christian gospel among its members.” The central government should also be playing a strategic role by creating a directorate within the DOT to oversee the movement of pilgrims during the Easter weekend; not only the ZCC, but also other denominations such as the International Pentecostal Holiness Church, St Jones and the Nazarene Church and other independent churches throughout South Africa.

The ZCC Easter weekend pilgrimage is dependent on vehicular traffic and the road infrastructure is insufficient to accommodate the pilgrims and other road users who travel to various destinations. The municipality understands this challenge since the number of pilgrims increase exponentially every year, but they lack the financial resources to address this challenge. The root demos in democracy stands for people but the study showed that citizen's participation in the planning and the execution of the pilgrimage is at a very low ebb. The citizens are relegated to the background thanks to the rule-centered culture of the church. This may be perceived as a weakness as well as a strength at the same time in that the church has built its own internal capacity over the years to handle the biggest pilgrimage on the African continent.

The church is an autonomous institution which has been empowered by the Constitution of the Republic of South Africa to exercise religious freedom as stated in Section 15 (1) that states: "everyone has the right to freedom of conscience, religion, thought, belief and opinion." In addition, Section 31 (1) states that "a person belonging to a cultural, religious, or linguistic community may not be denied the right to enjoy their culture, practice their religion and their language." The local government respects the church's belief system, but the belief system does not always chime well with the government approach and protocol. The provincial government and the municipality have the authority to operate and enforce laws outside the Zion City Moria premises; they have got limited say with the internal logistics such as parking as well as hazard identification and risk assessment where the responsibility is taken over by the church. Finally, there are areas where the church and the municipality jointly perform exceedingly well in terms of the pre-planning of the event, traffic management, disaster management as well as the debriefing session after the pilgrimage.

The study graphically demonstrated that the ZCC Easter pilgrimage is a force to be reckoned with in the African continent, but there is still room for continuous improvement in the joint planning and execution of the pilgrimage by both the ZCC and PLM. There are also lessons to be learned from Hajj and the Kumbh Mela since every pilgrimage has its own challenges, for example, pedestrian safety for pilgrim is an acute problem for the Hajj which the ZCC does not experience; it only the PLM that faces pedestrian challenges for the people who live within the vicinity of ZCM. The ZCC and the PLM could also learn from the other pilgrimages on how to manage communicable and non-communicable diseases during the pilgrimage. On the other hand, both the Hajj and the Kumbh Mela could learn the strategies of how to run a stampede free pilgrimage.

RECOMMENDATIONS

The study has shown that transport planning in South Africa is vehicular-centric. Other modes of transport could reduce the traffic congestion on the roads during Easter weekend. Saudi Arabia has attempted to adopt the proactive approach in their planning process. The government spent SR 6.5 billion to construct the 18km Mashir railway line. The Chinese-built monorail links Mecca with holy sites at Mina, Mount Arafat and Muzdalifah. There are 20 trains with a capacity of 3500 pilgrims per trip. The trains transport 72 000 pilgrims per hour, and over six hours move 377 000 pilgrims from Mecca to Mina, then to Arafat. The number of pilgrims who use the Mashir train has been reduced from its actual capacity of 500 000 to 377 000 as a safety measure. As an added benefit, the Mashir has created 4000 seasonal jobs for young people to work as security guards. Each train consists of 12 cars with a driver cab at each end. Each car is equipped with Passenger Information Display System, CCTV and a system to provide audio and visual communications between pilgrims and the train operating staff. These trains are designed to operate in automatic mode (driverless); however, each train has a crew of two drivers and additional passenger attendance available who are there during the Hajj operations (Saudi Railway Commission [42].

In comparison to the South African ZCC gatherings, the Islam Hajj at Mecca appears small. Mecca has the capacity to host only 4 million pilgrims per pilgrimage. Yet, the focus on ensuring the safe passage of the pilgrims has received a far larger focus than is currently the case in South Africa. Herman Bruwer, a South African advisor to the Saudi Railway Safety Commission said that the new system there is "very successful in that it saves the need for almost 53 000 buses on site". In his words, "PRASA should consider dedicated trains to Moria, combined with a dedicated bus route available to and from the place of worship". The ZCC should consider building passenger train platforms (at least 20 platforms which is shaded with overhead roofs) on the site which can accommodate at least 20 train coaches each. Each coach should be connected to a fresh water inlet, electricity socket and sewerage system. This way each pilgrim will have access to accommodation, fresh and clean drinking water and sewage for the duration of the pilgrimage. The proposed pilgrimage train should operate from Johannesburg to Polokwane. In addition, a light rail system from the Polokwane International Airport to Moria should established with the view to encouraging pilgrims to use airlines as mode of transportation. Many metropolitan areas are addressing transportation needs by establishing light rail transit systems. The ZCC, PLM, the taxi industry, railway companies as well as tolling company should work together towards the establishment of the pilgrim train. Tolling companies should not suffer from the "marketing myopia", they should not see themselves only operating toll gates, but they should also proffer a solution to transport problems in South Africa. Figure 2 is an example of a pilgrim train in Saudi Arabia designed specifically for the Hajj.

Figure 2: Along the Ride (Photograph by Amer Hilabi, AFP/Getty Images)

The ZCC has been in the transportation business for many years for the collective good of the community. It is highly recommended that the church should opt for vertical integration where they can become both the infrastructure owner and the operator of the train. In so doing, they would be able to create more employment for their members and to make the mobility of their members seamless; not only during the Easter pilgrimage, but throughout the year. Given the history of the ZCC; The Railway Safety Regulator will not hesitate to issue a safety permit to the ZCC.

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Towards a Parsimonious Information Management for Energy Retrofitting of Buildings

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Abstract

Throughout the world there are thousands of residential and public buildings that have been built during the reconstruction and rapid urbanization after the 2nd world war, particularly Eastern and Central Europe as well as in China. These are the most efficient target for mass improvement of their energy use through the improvements of façade insulation and windows. Advanced information technology (IT) - including building information modelling technology (BIM) - is not used very often in these renovations. Our hypothesis is that the use of BIM could be more efficient if it would focus on the essential information needs of the actors involved. The key idea of BIM - structured collaborative shared database of all required information - should be preserved but the model should be parsimonious. The paper presents the ongoing research in the context of a bilateral Chinese-Slovenian project with the goal of designing parsimonious information management for the retrofitting of existing buildings. The broader goal of the work is to study information modelling supporting works where a complete information model may not be needed at all and where a detail process definition - as outlined in BIM execution plan and related documents - would lead to overspecification, constraining the workflow.

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Keywords: building information modeling; energy efficiency; renovation; building process; parsimonious;

1. Introduction

Buildings are a major (up to 40%) user of primary energy everywhere in the world. Unlike with cars or electrical appliances - where the next generation can be more energy efficient than the previous one - buildings have a life span of decades or even centuries. The only way to improve the energy efficiency of the buildings is renovation. This is a goal in national strategies of both China and Slovenia (Smart Specialization). It is expected to make a major contribution in tacking climate change.

1.1. Renovation of buildings

In Europe, China and in many other countries in the world, there has been a serious housing crisis following the baby boom years after the Second World War. The crisis was being solved by a rapid construction of high-rise apartment towers and blocks. They were being built rapidly and economically, with several copies of each design, and in a time when energy was cheap. Such buildings can be seen at the outskirts of all major European and Chinese towns. The

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problem of those buildings today is that they are very energy inefficient, but also a grey and boring relics of some times gone by.

Since climate change issues got focus, massive renovation programs have been set in motion across the world. The main contribution would be the improvement of the façade, both optically as well as aesthetically. In the meantime, Building Information Modelling (BIM) technology has matured, which is driving renovations in the building field in recent years.

1.2. Building information modelling

BIM is an approach to building design and construction planning where a detailed, semantic, digital model of the new building is created collaboratively and shared to everyone involved in the construction process. Standards have been developed and implemented for the information structures and representation language of building information models. ISO 16739:2013 specifies a conceptual data schema and an exchange file format for BIM.

Because more and better information exists than can be captured in drawings, the designs can be better, more consistent, with fewer mistakes and surprises on the construction site. By conservatives estimates this reduced the price of construction by at least 10%, more liberal estimates are beyond the 20%.

BIM technology so far has (1) mostly been used for new construction, (2) research has been focusing on the digital model and (3) the conviction was that this model must be as complete and realistic as possible.

1.3. Research objective

The objective is to study how the BIM approach could be used in cases where the construction in question is not a new construction, where just some limited subset of information about the building is actually required and where the related process is repetitive. An example of such topic is energy renovation of buildings. Just a limited set of information is needed, several identical of similar buildings exist and the processes are repetitive.

Specific tasks include:

- Review how information technology, particularly the BIM approach is used for renovation, specifically for energy-efficiency renovation.
- Study of the renovation process and its information needs. We study how the process is performed, what is the knowledge base related to energy efficiency renovation, what are its information needs and how the process can be reused from a building to a building and from a renovation to a renovation. At some level of abstraction all processes are the same which introduces repeatability into the construction industry which is otherwise known for handling unique products (buildings) built in unique construction processes. This is unlike other industries where serial production is the norm.
- Develop a parsimonious subset of the building information model and not strive for an as-realistic- and as-complete-as possible information model. Models require effort for all the information to be compiled, however, the bulk of that information may not be needed in the downstream processes. In spite of not striving for a complete BIM model we will investigate how to use ISO standards and, if need is discovered, propose how standards should be extended for the representation of incomplete information needed for energy renovation.

2. Technologies for Computer Aided Energy Renovation

Information technology is used extensively in renovation projects. The list of technologies includes:

- GIS - Geographic Information Systems - they are used to store geographic and geospatial information in layers so that the spatial information can be created, stored, manipulated, analyzed, visualized and linked to the project. Besides the exact location and location information (such as coordinates and the shape of the terrain, satellite images etc.) it also connects to the municipality databases in order to present administrative constraints regarding the desired renovation from the building as well as location perspective.

- Laser scanning and remote sensing - these technologies are usually the quickest and the most accurate step towards digitalization of physical objects. They are used to accurately capture inaccurate boundaries of the buildings (residential, nonresidential), which is especially valuable for the historic buildings without accurate plans or building permit documentation. Even with documentation it is often used to capture object as-is as opposed to the as-should-be reality of the AEC project documentation.
- Accumulative and solid modelling - is a technology (it can also be presented as a set of principles) for (computer) engineering of 3D models (solids) as a presentation of (physical) objects. As it is typically used throughout the whole project design lifecycle, in the context of renovation, it is usually the successor of laser scanning and the logical and necessary step in the process of scan-to-BIM, resulting in the foundation for BIM.
- BIM - Building information models, modelling and management. It is well known and was discussed briefly in Section 1.
- Computational fluid dynamics (CFD). CFD is used for the detailed analysis of the indoor climate in buildings for the evaluation of the performance of the HVAC systems, the prediction of thermal comfort conditions and the design of special purpose ventilation, heating and cooling systems according to the geometrical design of the building (building orientation, openings, glazing surfaces etc.). CFD simulations are especially important for the restoration of buildings and can be used for two important purposes: 1) to explain what was happening before the renovation and therefore identify problems in initial design, and 2) to validate the improved and refurbished design.
- High-throughput computing (HTC, for simulations) and cloud computing (for HPC, CDE). Both HTC and HPC are used for the time and power intensive tasks in order to obtain, analyze and validate results in the reasonable time frame. While HTC is aimed at tasks which can be parallelized, HPC is promoting and speeding up all other duties. Both of them are an important enabler of the use of CFD technologies in AEC as those analyses are otherwise too time consuming.

The technologies have been listed roughly in the order in which they are used.

3. Renovation processes

Renovation processes have been studied in greater detail by several research teams and they are also taking place in the practice.

In the TES project (Cronhjort, 2009) the renovation process has been broken into the following phases: building examination - digital measurement - planning - off-site fabrication - on-site assembly. The approach used pre-fabricated elements to attach to whole or large areas of façade which called for a rather detailed model of the outside of the building. The project is implicitly aware of the tradeoff between BIM complexity and renovation requirements.

BIM technology is taken for granted as a welcomed tool in renovation projects. Yin (2010) claimed that BIM plays important roles in the energy & cost savings of the building’s life, particularly in the stage of building management - it enables simulations in the building’s digital twin.

Di Mascio and Wang (2013) claimed that particularly Building Information Modeling (BIM), makes the design, organization and construction of renovation projects manageable and improve them. They see benefits in three dimensions of sustainability, environmental impact, and economical and social benefit.

Aldanondo et al. (2014) addressed the problem of industrialization of energy renovation of apartment buildings. It limits the BIM information needs to the external dimensions of the building and it also finds the need to project to the outside envelope some structural characteristics of the building. The paper (ibid.) presents an implicit ontology that is useful as a point of departure for our work. It defines a renovation process that has five stages: building geometry generation, building analysis requirements characteristics, renovation specific design, manufacturing of pre-made components and renovation on the building site. It differs from our work in the fact that it deals with prefabricated elements for the improvements of building characteristics.

Hammond et al. (2014) studied how professionals use BIM in retrofitting and renovation and how it affects their practice. They investigated a renovation process that had the goal of utilizing BIM "in as many areas as possible" with a view to comply with LEED rating system. They found that the information sharing and collaboration features of BIM made it a great tool for the renovation of existing buildings, regardless of the scope of the renovation. Also useful was energy simulation and conflict resolution. It can be assumed that a rather thin BIM model suffices for that, however, the work did not focus on establishing a standard model or process.

Khaddaj and Srour (2016) defined a renovation process with three stages: pre-energy modelling stage, energy modeling stage and refurbishment options stage. They identify challenges related to the use of BIM for renovation: multi-disciplinary nature of participants, the timeliness of the exchanges, and the wide array of technologies. In the research agenda, they pointed out that both Information Delivery Manual (IDM) and Model View Definition (MVD) focus on new construction and not existing buildings. Construction Operations Building information exchange (COBie) standard does not include architectural and structural components that could be relevant for refurbishment. They concluded that "BIM is still immature for its full adoption in refurbishment projects because of technical, informational and organizational complications". Our parsimonious approach should be addressing these complications.

Scherer and Katranuschkov (2018) coined the word "BIMification" for a process where BIM technology is used extensively in the design and implementation of the renovation processes. They propose a structured approach for the creation of a BIM model of existing buildings to be used in retrofitting. The renovation process is split into anamnesis (collection of data about the building), diagnosis (analysis and interpretation of the collected data) and therapy (designing and implementing the retrofit). As the approach is generic it creates a rather complex, thick BIM model which, in our view contains more data than needed for our class of buildings.

4. Lessons learned so far

The issues have been studied in ISES project. This was a H2020 project from EU FP7 running from 2011 to 2014. ISES was developing ICT building blocks to integrate and complement existing tools for design and operation management into a Virtual Energy Lab capable of evaluating, simulating and optimizing the energy efficiency of products and facilities, in particular components for buildings and facilities, before their realization and taking into account their stochastic life-cycle nature (see Figure 1).

Fig. 1. ISES Virtual Energy Lab.

Among the results of the project was also the energy-aware decision workflow starting early in the design phase affecting the energy performance of the building being validated with powerful cloud-based services using developed pre- and post-processing tools. All of them were consolidated into extensible open-source virtual lab kernel.

Nevertheless, the project showed that that are a lot of challenges when performing design analyses. While some of them are considerably less severe nowadays as they were in 2014 (such as shortage of BIM experts or lack of BIM and other relevant standards on national and world levels) there are still issues that have yet to be resolved. A lot of them are related to the essence of BIM and what BIM actually is to a project group. ISES project showed that not all BIM models can be used for every analysis and in any stage of the project/project design. While there were parts of the model that were mostly not detailed enough (such as HVAC which usually lacked important attributes), models for the most part were too detailed, complicating analyses and resulting in non-converging CFD equations, time-consuming processes and unusable results.

The ISES project showed that there is a need for a reusable BIM solutions for repeated projects tasks, one of the most important ones being a transition from architectural to (simplified) energy-specific model views.

Initial studies of the process and information analysis have been performed by a few master theses at the University of Ljubljana. At one side of the spectrum is the work by Todorović (2009) who created a detailed BIM model for the renovation of a building. On the other hand, Radošević (2015) was finding simplified SkectUp geometry of the buildings sufficient for the insulation, shading and energy requirements estimates. Quantity and costs estimate for a particular building have been established through the use of software by a particular insulation material manufacturer. This software is not general-purpose BIM modeller but specialized software that lacks several features of BIM. However, its information needs are a very good example of what information is indeed needed for renovation with particular technology. Stamač (2017) performed a renovation of a typical building targeted in this project and his analysis revealed that a rather limited set of data is required to do the analysis. That work too presents a good context for the study of information needs.

5. Conclusions, discussions and future work

We have presented the motivation, goals and points of departure for a Chinese-Slovenian project that should allow for industrialized renovation of residential buildings using BIM concepts and technology. Literature study and previous work show that the information requirements for energy renovation and very different than for new construction and so is the process itself.

Further work in the project will be focused on the following. (1) study the documentation of existing renovation projects, their information needs for analysis and the design and renovation process, (2) perform a survey in the industry that is involved with renovations, particularly related to decision making in design and renovation, (3) propose an information model that would address the needs established in 1 and 2 and match it against standards and applications including IFC, BIM modellers, IDM and COBIE, (4) establish a generic process model that would serve as a guide for industrialized construction, (5) test 3 and 4 in a real project, (6) study general lessons about the use of BIM approach, BIM technology, BIM collaboration in a setting that requires partial, simple, or parsimonious product and process models.

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Traceability for built assets: proposed framework for a Digital Record

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Abstract

In May 2018, the UK Government published an independent review of building regulations and fire safety in response to the tragic fire at Grenfell Tower. The *Hackitt Review* identified the need for traceability; a 'golden thread' preserving critical information about design intent and the as-constructed building in a proposed Digital Record (DR). This study proposes a framework for a DR for traceability of all built assets, new and existing. Three structured workshops including four working groups were held with industry practitioners and academics to collaboratively establish definitions of traceability and a DR. The key requirements of the DR were identified through development of 63 use cases. Building on traceability systems research in other industries, a framework for traceability of built assets was developed and analysed with industry. The framework, containing both information chains, supply chains and unique identification of traceable items, is outlined in this paper and its key components are discussed along with identification of areas for further research.

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Keywords: digital record; traceability; information chain, supply chain, construction industry; Hackitt Review.

1. Introduction

In June 2017, a tragic event resulted in the death of 71 people when a publicly-owned, high rise residential building in London, United Kingdom (UK) caught fire. Subsequent investigations identified systemic failures [1] as contributory factors in the tragedy. This prompted a review of building and fire safety commissioned by the UK Government – the *Hackitt Review* [2] identified the construction industry as slow to adopt traceability and quality assurance techniques in comparison to other industries and recommended a Digital Record (DR) for higher risk residential buildings (HRRBs) to ensure stakeholders have access to accurate, up-to-date information throughout the building lifecycle. Three reasons why traceability is required in the construction industry emerged from the Hackitt Review: i) to provide confidence/assurance and the ability to check that 'things are as they should be', the correct product has been installed correctly, complies with the relevant standards and has been maintained appropriately; ii) to ensure the required information is available to facilitate action in the event of non-compliance; and iii) to provide the ability to access all information about a product, offering wider potential benefits such as a more effective product recall system, better quality control, improved procurement and support for continuous development and learning from experience [2].

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Traceability of built assets is challenged by both the particular nature of the construction industry and built assets. Some of the key challenges include: very long project and asset lifecycles exceeding 60 years; the complex information chain from requirements and design, through construction to in-use (including design and ownership changes, product data, and adaptations); the varied nature of procurement processes adopted; difficulty in identification and tagging of products; and varying granularity of products and information.

The aim of this study is to establish a framework for a DR for the construction industry as set out in the Hackitt Review. It is achieved by: developing working definitions for traceability and a DR validated by stakeholders; establishing the components required for a traceability system (drawing on existing research and application in other industries); and testing and validation of these proposals with stakeholders. The scope of this study includes all types of built assets, new and existing across all stages of the asset lifecycle whether for new build, renovation or retrofit. Increased traceability in construction is proposed to lead to improvements in accountability and compliance with regulations and the ability to support product recall, resulting in a safer built environment for its occupants.

Section 2 discusses traceability in the construction industry; section 3 presents the workshops conducted for this study and highlights the results; section 4 describes the proposed framework and the results from the workshops; and section 5 provides discussion, conclusions and next steps for the research.

2. Traceability in construction

While no formal definition for traceability is provided in the Hackitt Review, a definition is required in the context of the construction industry to: i) support shared understanding of objectives; ii) guide development of proposed solutions; and iii) provide a test to evaluate any proposed solution. There is currently no comprehensive, industry-wide scheme to support traceability in the construction industry in the UK. A number of publications discuss aspects of traceability in construction, however, most lack a formal definition. Katenbayeva et al., [3] simply state it "is the ability to follow information related to a product through its supply chain" (p. 3) providing a number of uses: quality and safety, minimising scandals that damage company reputations, improved supply chains, and enhancing trust. Kamara et al., [4] state "client requirements have to be presented in a manner that will facilitate: (…) [t]he traceability of design decisions to original requirements throughout the life-cycle of the facility" (p. 17). Hao et al., [5] link traceability to client requirements and initial building design where the number of changes throughout a construction project can be reduced when accurate client requirements are captured at the outset and effective traceability is embedded thereafter.

The food industry has a more advanced system in place for traceability and is very effective in holding the industry to the highest standards of food safety and quality assurance. Building on previous ISO definitions, Olsen and Borit [6] define traceability as "the ability to access any or all information relating to that which is under consideration, throughout its entire lifecycle, by means of recorded identifications" (p. 144). No such definition exists for traceability in construction; establishing one was a key objective of the research in this paper.

There is a body of research investigating the application of technologies such as radio frequency identification (RFID) tags within the construction industry that cite traceability as one of the potential benefits of adoption [7] but much of this work is focused on supply chain efficiency, logistics and inventory management and not directly concerned with addressing many of the issues highlighted in the Hackitt Review.

The Hackitt Review sets out the need for a 'digital record' for buildings that would provide a 'golden thread' of information that preserves design intent, manages changes and ensures stakeholders have access to comprehensive, up-to date information about the building. The relationship between the DR, traceability and industry initiatives already in place, including UK-mandated BIM Level 2, needs to be established requiring a definition of the digital record.

3. Workshops

Three workshops with academic and industry practitioners were held to develop and agree a definition of traceability for construction and a definition of a DR and to examine and evaluate these in more detail through the identification of a series of use cases. The first workshop served as a pilot and consisted of four academics with expertise in construction, architecture, the built environment and computer science; the second workshop consisted of nine participants made up of industry practitioners from across the following professions: software developer, construction information provider, solicitor, designer, architect and home builder; the third had eight participants from manufacturing, legal, software development, fire safety, facilities management, compliance, installation standards and specifications. The workshop participants found the Hackitt Review definition of a DR lacked sufficient detail to form a working definition. The first and second workshops were asked to develop propietary definitions which were then presented, discussed and refined in workshop three. Next, they were asked to consider and identify use cases that would require or benefit from the existence of a robust DR. The use cases were used to further refine and test the definitions developed, scope the requirements for implementation of a DR and to explore potential real-world implementation.

Based on definitions for a DR from the Hackitt Review [2] and those developed during the workshops for this study, the authors propose the following comprehensive definition: *A digital record provides traceability through a secure, immutable and auditable electronic record of all required information, actions and decisions taken to assess and achieve compliance of a built asset with relevant standards and regulations at a point in time. It must record stakeholder and compliance requirements, design intent, procurement of materials/components and construction together with the testing, validation and verification processes undertaken, capturing their outcomes in order to provide a complete decision-trail. The record will include physical asset and performance data of all components and support traceability of provenance from raw material state through manufacturing, installation, maintenance and disposal, detailing who did what, when, why, how and to what specification. The digital record must be accurate, traceable, appropriately open, non-proprietary, searchable, and show clear delineations of risk ownership.*

An adapted version of the Olsen and Borit [6] definition of traceability was adopted for built asset traceability: *The ability to record all required information relating to that which is under consideration, throughout its entire lifecycle, by means of recorded identifications.*

These offerings provide idealistic definitions for a DR and traceability and require an authoritative body to define critical aspects such as what the 'required information' is for each type of built asset, recognising they will likely differ between types and at different stages of the asset lifecycle. However, these definitions serve as a point of departure for the industry to consider and improve.

Use cases were identified across the three project lifecycle phases of design, construction and in-use for both new and existing built assets. 63 separate use cases were identified. Some examples of these include: design (e.g. the transfer of initial brief from client to architect; proposed renovations to a building to achieve environmental targets); construction (e.g. tracking changes to the initial design; recording repairs); in-use (e.g. scheduling periodic safety inspection; the sale of an existing building). Three use cases were developed in detail: an energy efficiency project for an existing school; construction of a new HRRB (the focus of the Hackitt Review); and product recall of a gas boiler. The use case development and review activity resulted in: i) a clear understanding that a DR should provide the mechanism for achieving the traceability of information and products required in the industry; ii) an appreciation of how traceability systems already implemented for automotive and food product recall could inform development of a framework for a DR in construction; and iii) definition of a set of use cases that serve to define the scope and requirements of a DR and can be used to test and evaluate proposed solutions.

4. Proposed framework

The purpose of a DR is to provide traceability throughout the lifecycle of a built asset [2]. The Hackitt Review recommends the adoption of a traceability system and learning from other sectors where traceability is more advanced. Traceability in manufacturing and food sectors is primarily concerned with identifying the source (e.g farm), input materials and supporting full backward and forward tracking, to determine the location and life history in the supply chain of a product [8,9]. For a built asset, such a system would provide the ability to answer questions such as, "Where did this product come from, what is it made of and does it meet the required standards?" (backwards traceability); and, "Who sold all the products from this batch and where are they now?" (forwards traceability). The Hackitt Review also highlights the importance of recording the original "design intent" so that any subsequent changes can be identified. A DR framework for built assets must therefore support traceability of requirements and corresponding design solutions. Sectors such as safety-critical software applications require traceability across requirements, proposed solutions, verification and validation [10]. A holistic framework is proposed encompassing both information and physical chains over the lifecycle of a built asset and the relationships between them as demonstrated in Fig. 1.

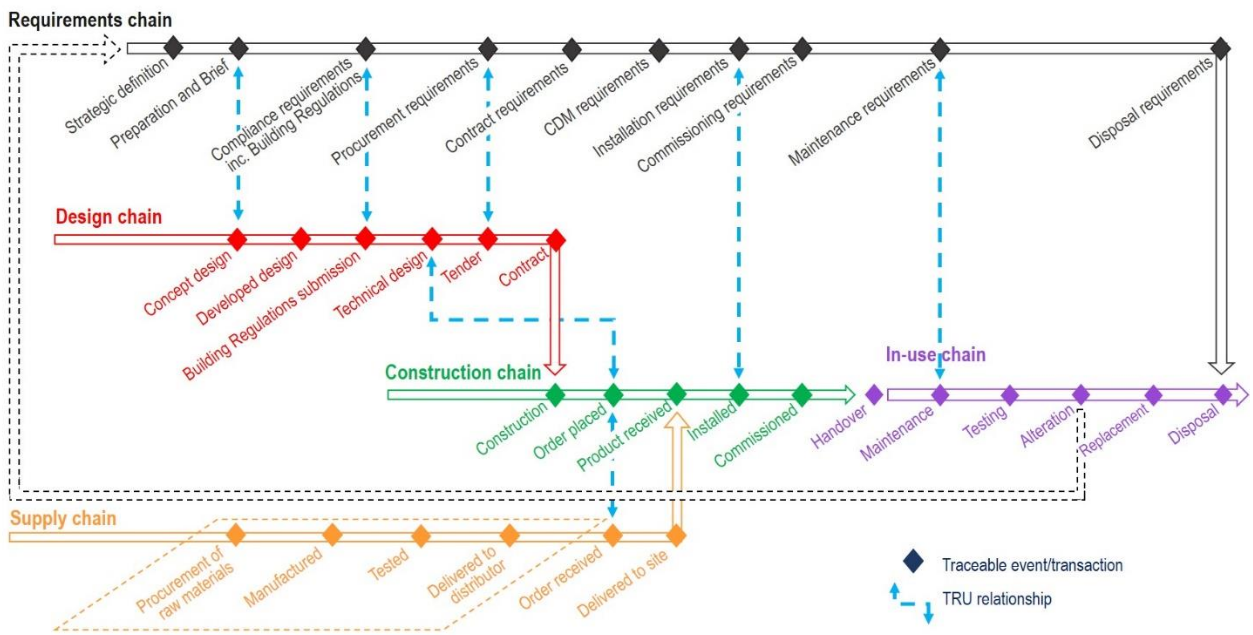

Fig. 1. Framework for a digital record in construction

The ***requirements chain*** includes requirements set by clients and stakeholders (typically captured in briefing documentation) and requirements set out in legislation (e.g. building regulations, health and safety legislation) and standards. The ***design chain*** records the 'design intent' – proposed design solutions in response to requirements. The ***supply chain*** includes raw materials, manufacture, testing, sales and distribution of construction products. Depending on the type of product being procured, certain activities will take place either before or after the order is received as indicated by the activities in the dotted box of the supply chain in Fig. 1. The ***construction chain*** includes selection of products in response to design solutions, the ordering and delivery of products and materials, installation, site-manufactured products, commissioning and certification. The ***in-use chain*** includes periodic testing and maintenance of the built asset and its constituent parts (either to meet legislative requirements or good practice), repair or replacement of components; adaptation and alteration of the built asset, and changes in ownership, tenants or occupiers. During the in-use chain, alterations will initiate new requirements chains, creating a circular model as indicated by the dotted arrow from *Alteration* in the in-use chain to *Strategic definition* in the requirements chain.

Olsen and Borit [6] set out the components of a food traceability system as: a definition of traceability; a definition of a traceable resource unit (TRU) – the item about which traceability information needs to be recorded; and mechanisms for identifying TRUs, documenting transformations (connections between TRUs) and recording the attributes of TRUs. A New Zealand feasibility study [12] defined the requirements of a traceability system aimed at reducing the use of non-conforming products in the construction industry as: unique IDs built on international standards; standard product marking technologies; aggregation of units, including parent-child relationships to establish links between units; data capture supporting access to additional information such as product description and provenance; definition of supply chain events (points in the chain where each shipper and receiver is required to validate units as they change hands); data transfer (how data is transferred and stored and the ability to access data by users). We adopt and extend these components in the definition of the DR framework.

Traceable Resource Unit (TRU) is a well-established general term in literature [6]. In food traceability systems, this is typically applied to trade units (a case, bag, bottle, box), a logistics unit (pallet) or production unit (batch). These are applicable to the supply-chain for construction products, but for a complete construction traceability approach we extend the concept of a TRU to include traceable 'units' for each of the chains identified. TRUs for requirements and design are non-physical units, which need to be represented digitally to support traceability. TRUs for supply, construction and in-use units will include physical products, components and materials. To support traceability of decision-making and certification, TRUs should also be considered for actors (individuals) and organisations.

The granularity of TRUs will vary from the very small (e.g. an electronic component within a larger piece of equipment) to whole-building scale (e.g. for compliance with energy performance requirements). Building modelling methodologies and classification such as the hierarchy set out in the Uniclass 2015 classification system [13] could be adopted to define the granularity of TRUs for built assets.

Traceability requires recording key relationships between TRUs. The 'composition' relationships must be recorded between the TRUs (e.g. a domestic hot water system and its component products such as radiators, valves and pipes). The 'fulfilment' relationships between requirements, design solutions and installed products must also be recorded along with validation and verification relationships. To support both forward and backward traceability both ancestor and progeny relationships need to be recorded. TRUs must be traceable across organisational boundaries.

TRUs must be uniquely identified, requiring a system that implements identifiers that are *unique within the context* where they are used [6]. Identifiers must be persistent and usable for the lifecycle of the building and ideally offer a degree of extensibility to support future (as yet unknown) data requirements. Systems such as the GS1 Global Trade Item Number (GTIN) [14] or research into unique product identifiers [15] could be adopted. A system similar to ORCID persistent digital identifiers for academic researchers [16] could be considered as the basis for an identifier system for actors. Requirement and design TRUs will be digital objects, which can support inclusion of unique identifier (UID) codes as attributes (e.g. as a property of an element in the BIM model or specification). TRUs for physical products within the supply, construction and operation chains can be carried using bar codes, QR codes or RFID tags. Consideration needs to be given to where data about the TRU is stored and how it is updated.

As TRUs move through the various chains, information needs to be recorded at key points in time which we term as 'transactions' indicated by diamonds in Fig. 1. Traceable transactions will include: changes in ownership or responsibility (a product is delivered by the supplier to site and the contractor takes ownership, the building is handed over to the client); the fulfilment of a requirement or design (the contractor places an order for a product to fulfil part of the design intent, the design definition progresses from a performance specification to a prescriptive specification); verification and/or validation activity (a product is tested and certified against a standard, a system is commissioned, works are inspected); information transactions (the architect issues design information to the contractor for the purpose of construction); and transformations within the supply and construction chains (components or materials are combined in the creation of a product, products are incorporated into the building). These transactions need to be uniquely identifiable within the DR, therefore, require UIDs. Metadata about the transaction needs to be recorded, including purpose, date, time and the parties involved. The precise data to be recorded will depend on the transaction type. At each transaction, key information must be recorded about the TRUs included within that transaction. These attributes will differ depending on the type of TRU and the transaction and can potentially be defined from information contained in BIM information exchanges. The NBS BIM toolkit [17] offers a potential starting point to define TRUs and required attributes, particularly for the design chain.

Storage of the traceability data outlined above needs to support: access by project stakeholders; trust (that the data is accurate and has not been altered); security (preventing unauthorised access to sensitive data); privacy (protecting personal data); and long-term access for the lifecycle of the building. The Hackitt Review recommends that the DR be "open and non-proprietary and with proportionate security controls" ([2], p.60). These requirements suggest distributed ledger technologies (DLT) may offer suitable plaftom to host the DR and will be explored further in future research.

5. Discussion and conclusions

The Hackitt Review identified significant failings in UK processes for compliance, quality and accountability in the construction and alteration of HRRBs. The review recommended a digital standard of record keeping (a digital record), supporting a 'golden thread' of information (traceability), but did not give explicit and implementable definitions for either. Other industries, such as food, manufacturing and automotive have implemented supply-chain traceability systems to improve product quality and safety and support product recall. The need for traceability of requirements in sectors such as safety-critical software is also well-established [10]. Traceability research in the construction industry has focused on client requriements [4] and the application of RFID tagging to support construction supply chain management and logistics, tracking and tracing of materials, site quality control, inventory management and lifecycle/facilities management [7]. Based on the definition of construction traceabilty proposed here, we suggest that implementation of a comprehensive DR to support full traceability of built assets must cover both the information supply chain (requirements and design solutions) and product supply chain (manufacturing, construction and in-use) and the critical relationships between them. The components and requirements for traceability systems set out in Olsen and Borit [6] and Dowdell [12], have provided a basis for the development of the DR framework set out in this paper. The framework and accompanying definitions for construction traceability and DR have been evaluated in a series of workshops with industry experts against a set of use cases.

Further work identified by the authors and through the workshops includes: additional industry input and review to validate the proposed framework; detailed specification of the TRU attributes to be recorded (mandatory and best practice); development of a comprehensive list of transactions across all information and supply chains; identification of a suitable UID and carrier system; identification of the existing processes and information systems that could be incorporated into a DR. There is substantial research to be undertaken to define the technical implementation (platform) of a DR, including the technical approach and architecture, ownership and sharing of data, and definition of how existing systems, data records and processes (e.g. BIM) are integrated. Finally, consideration needs to be given to the strategy by which industry adoption will be secured, the degree to which this is mandated (as in the food industry), the need for any regulatory bodies and the balance between complexity, cost and ease of implementation and adoption.

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Urban Consolidation Centre – In Context with Construction Consolidation Centre a Comparative Analysis

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Abstract

Construction industry toiling with the adversarial relationship, competitive market, and low overall revenues continues to investigate, study and implement various frameworks that can enhance the relationship among the parties, standardize processes, and enhance productivity and profit margins. The paper takes into account the concept of lean manufacturing/production of waste minimization by the concept of UCC which dates back to 1970s, one of oldest and still functioning UCC is in Tenjin, Japan which was started in 1978. The study is done on UCC's at a different geographical location across the world trying to identify the factors that contribute to make it a success or failure. Based on the study-specific questions are prepared to analyse UCC's implementation in Asia's largest slum Dharavi situated in Mumbai the Financial Capital of India and will seek an answer to the question - can it help enhance the makeover of Dharavi

Keywords: SHM; Building Construction; Technology; India; Construction Management; Building Material.

1. Introduction

Construction is governed by low-profit margins and various studies had been done and continue in the future to adapt and implement various systems that can enhance the productivity and profit margins. One such approach is to explore the transfer of lean manufacturing/production from the Japanese manufacturing industry to the construction. The Japanese automobile Toyota developed the philosophy "Lean". Lean manufacturing concentrates on adding value by waste minimization ("MUDA"), an impossible task, and overburden on employees ("MURI"), unevenness, irregularity, non- uniformity ("MURA").

It is evident that the Construction industry generates tons of waste. As per NBS website the Department for Environment, Food and Rural Affairs (DEFR). It reported in their Feb 2018 edition of "UK Statistics on Waste" that in 2014 the UK generated 202.8 million tonnes of waste.

Table 1UK statistics on waste generation

Government Organization Report (CDE) Wastes	*Data*

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Construction Demolition and Excavation. "(DEFRA) Department for Environment, Food and Rural Affairs"	59% of 202.8 million tonnes
BREEAM Construction industry accounts for approximately	55%
OPERATIONAL WASTES (carbon emission)	
Building operation	50% of the total CO2
Global Industrial carbon emission due to the manufacture & processing of five key building materials:	
Steel	25%
Cement	19%
Paper	4%
Plastic and Aluminium	3%
The industry is also the primary consumer of the building material	The Industry consumes: Aluminium - 26% Steel - 50% Plastic - 25%

[1]

Therefore researchers are trying to optimize the wastes. These being the reason which attracts researches from the construction industry to try and minimize the waste at different stages/phases of construction. Construction has different stages/phases. One such stage/phases identified is the supply of materials for construction (that accounts for waste generation)i.e transportation and stacking of materials to the construction site. The fact is materials are wasted during transportation due to handling. The "MURA" which can be attributed to the reason for the existence of the seven wastes. It can be inferred that it leads to MUDA. For example, construction requires specific materials to be transported and stacked at the site as per scheduled requirement. Overstacking leads to unnecessary piling of material and not fulfilling the requirement which results in waiting. The construction activity can be adversely affected due to non-availability of materials on site which can result in project delays. Both over stacking and waiting are wastes. To avoid such scenario JUST IN TIME approach "KANBAN" came into picture which focuses on delivering the right material, at right quantity and at right time.

The transportation of materials offers a great challenge in Urban Areas (Urban area is the human settlement which is defined as having high population density & infrastructure of the built environment). The traditional method of freight delivery cannot address the intensification of transport freight through the inner- city areas as it may results in traffic congestion, environmental devastation, increased noise level and increase the probability of accidents. The freight delivery is based on the concept of direct delivery of the products to the recipient. Every delivery made by large size trucks in the city Centre is independent and causes traffic congestion thereby increasing the exhaust emission and environmental degradation. In recent years "Urban Consolidation Centre" has proved to be an alternative against traditional freight system. The concept of UCC dates back to the 1970s, one of the oldest and still functioning UCC is in Tenjin, Japan which was started in 1978. UCCs are among the emerging trends in most of the developed countries. Germany has about 12 UCCs operational. The countries like England and Italy have also opted for UCCs.

2. Literature review

The literature review is done to get the overview of Urban Consolidation Centers and it's applicability some of the places where it had been operational are covered. The objective is to find out it's working and operation and try to figure out how they function, a basic requirement, cost aspects etc. As per the understanding, the Construction

Consolidation Centre is the subset of Urban Consolidation and therefore the study is beneficial to have a greater understanding of the concept

It's a concept of logistics taking in the basic of Japanese philosophy. The problem in developing logistic management and find answers on how to improve the construction logistics in the urban area. The aim is to reduce the cycle's of transport and improve the time efficiency of delivery.

One of the major obstacles in obtaining the effective operation of construction logistics in the urban cities is the fact that they are urban cities having narrow streets, continuously growing traffic and narrow streets. More effective logistics will result in less traffic, lower sound and air pollution levels, which can be achieved by collaboration in the construction business. Although the collaboration is difficult to achieve due to fragmentation and adversarial nature of the business. If this redundancy is removed it can result in improved logistics in the construction sector.

Logistics gives economic advantage due to improved work efficiency. As per Council of Supply Chain Management Professional (CSCMP): Logistic Management is a part of supply chain management that is responsible for planning, implementation and controlling the efficiency, effective in both forward and reverse flow, storage of goods and services and also relating to the information between point of origin, point of consumption so that it could meet customer's requirements.

The city centre is under a large amount of pressure due to a large amount of traffic. The streets are narrow with a large number of vehicles, overcrowded pedestrians this all factors give limited space for freight transport. The figure below depicts the activities that are commonly performed in logistics management.

As stated above the obstacles and adversarial nature of the construction are not the only problem. The interview conducted at Stockholm revealed that many recipients was sceptical about the construction of permanent logistics centre in the outskirts. The capital size and the number of construction projects at the current and future situation were the reason for scepticism. According to Skanska's production manager, Simon Lindholm "the use of logistics centre would evidently happen if the number of projects was of the same type and in a range of each other". This statement was equally agreed by Eva Sunnerstedt at Stockholm of Environment and Health Department. The scepticism was due to large centre however many agreed for the temporary localcentre at a different scale of large projects. Norra Djurgardsstaden and Hammarby Sjostad are two such examples. The report depicts that the number of transports was reduced by 30- 40 %. [2]

3. Methodology

The methodology adopted is the comparative analysis of different construction consolidation centre and interview conducted on Quantity surveyor & site engineers, getting a response from the questionnaire. The responses were taken from people working in the construction industry, site engineers, students having relevant knowledge on the subject matter and the faculty members. The responses gathered were binary that is in yes or no and in some questions option of can't say and not sure were provided. The analysis is done by Chi-square method of hypothesis testing.

The following questionnaire was prepared to get the views/opinion on the specific question.

The questionnaire consists of three parts:

1. The first part to get information about the individual participating in the questionnaire. The information like :
   I. Their current working under which party govt. , private etc.
   II. Size of the project.
   III. Experience
   IV. Andthe type of project
2. The Second section focuses on Construction Consolidation Centre – The basic understanding and tries to get the views of the professionals on the following attributes:

Attributes/ variables	Reference
Size of the project for use of CCC	[13]
Financial viability.	[21][25]

Administration of CCC.	[21][13]
Financing party of CCC.	[21][13]
Secrecy and sharing of information.	[21]
Addressing questions regarding liability, theft etc.	[21]
Application of CCC in the long run.	[21]
Advantages of CCC.	[13][21][14][3][1][10][25]It's used
in the long run.	[13][21][14]
The party who should take responsibility to administer CCC.	[21]
The rigidity of Construction in the application of different concept	[3][21][9][10]

3. The Third section on the questionnaire tries to access the views of professional on “Mumbai Dharavi” can CCC be beneficial:
    I. The advantage of CCC in Mumbai- lower traffic, reduce pollution
    II. Can it be used for a longer period?

4. Discussion

The study done revealed that as per India industry small size of the project is not financially viable and due to the competitive market of industry there is fear that the secrecy of information can be revealed to the third party & the rigidity of construction industry to change remains the main drawbacks.

The solution can be increasing collaboration and cooperation, training, education, standardization in the sector. Another possible solution can be the use of trial projects. Further, the logisticscentre can be used for the long run that is it could be either permanent (serving for construction projects over a long period of time) or temporary serving single project for a limited time.

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Usage of project management methods, tools and techniques in infrastructure projects

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Abstract

We are witnesses of projectification of our world. Projects are evolving daily, in faster, bigger and more complex manner, requiring project management to adjust to these changes adequately. One of the major help project managers and their teams have in decision making, planning, monitoring, organizing and doing their everyday activities in general are set of different project management methods, tools and techniques. They are supposed to increase overall project success, which is often not the case, especially on projects of large infrastructure nature. The main aim of this article is to investigate which project management methods, tools and techniques, as well as project management methodologies and standards, managers of infrastructure projects use (due to their company and/or project requirements, knowledge or habits) in accordance to their perceived usefulness in context of Republic of Croatia. This kind of research may help in better targeting of those project management tools that really do make the difference in special contexts. This is especially important in world where added value to projects fulfilment is appreciated more than ever. Methodology used in this research was comprehensive literature review on the field, survey and statistical analysis. Results of the research may be useful both to project management scientists in directing their future research on the field, as well as project management practitioners and educators in usage and development of knowledge, skills and experience of working with the most effective methods, tools and techniques.

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Keywords: infrastructure projects; methodology; methods; project management; techniques; tools.

1. Introduction

Projects are becoming more challenging than ever before with the evolution of globalization, political realignments and rapid advance of information within firms [1] as well as general growth of economic and social demands. An effective strategy for overcoming those challenges may be found in engagement of information technology (IT) solutions in project management profession, which is already happening in development of virtual teams or application of neural networks. However, main problems of IT solutions remain the well-known "garbage in = garbage out" [2], so they remain only a category within the area of possible project management methods, tools and techniques (MTTs). MTTs seem to be an important project success factor. The application of the best standards and MTTs on project has positive effects on the overall project success [3]. Many projects fail to fulfil targeted budget, deadline or quality requirements, as well as overall project goals and contribute to organizational strategy. This problem is in focus on a special way if we talk about large infrastructural projects, which have even larger set of project success criteria to fulfil

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than those of "iron triangle". Therefore, it is purposeful and meaningful to find out how can project management MTTs and best praxes help project managers in leading their complex project endeavours towards successful outcomes. The main aim of this research is to find out which project management MTTs, as well as project management methodologies or standards, project managers use in managing infrastructure projects, as well as how useful they consider them to be. The fulfilment of the research goal will contribute in building awareness of relationship between usage and usefulness in order to direct future performances on the field. The goal is reached throughout research methodology explained below.

First step was to define relevant MTTs, methodologies and standards used in today's world of project management. This was undertaken through desk research - literature review of the relevant publications on the field. Then, a survey was undertaken within one group of infrastructural project managers – those of water projects. The sample was asked to give their insights on the level of usage and usefulness (efficiency) of each of methodology, standard, and MTT from the list created in the first step. In addition, they were asked whether they think that some new solutions on this field are needed while managing projects. The results of the survey are given as an output of descriptive statistical analysis and grouping within categories of those inputs that are used most often, frequently, and rarely. Research results are then elaborated in context of today trends, other researchers work, and answers on the meaning of the picture of present state on the field. Finally, conclusion remarks and guidelines for further research are given.

2. Literature review

Project management methodologies and MTTs are significant project management success factor, and therefore, one of the enablers of project success [3]. Project management methodology is usually defined as a set of methods, techniques, procedures, rules, templates, and best practices used on a project. It is commonly based on a specific project management approach, that defines a set of principles and guidelines, which then define the way a project is managed [4]. The most common and well-known project management methodologies and standards within European context (especially in South East Europe) are PMI's Project Management Body of Knowledge [5] and IPMA's International Competence Baseline [6]. While using a certain methodology (or while managing a project without the official one), project managers must use some of project management tools and techniques, in order to fulfil their tasks and manage projects more effectively, organize their work, gather data and communicate.

There are numerous project management methodologies and MTTs nowadays. In order to find out an initial list of those that will be tested, authors did a comprehensive literature review. For the need of this research, the division of [7], followed by [8], which authors presented in their work as one element of project management success factors breakdown [3], was taken. Ref. [7] divided methodologies and MTTs for project management on six groups: project management methodologies, project management software, project management tools, decision-making techniques, risk assessment tools and information communication technology (ICT) support tools. From the initial [7]'s list, some elements were taken out, because they were not applicable in national context. Also, some of the elements that may had been significant in this context were added based on the review of relevant literature [9-12], forming the final list which was then an input to a questionnaire. Which of these methodologies, standards and MTTs are used, and which is their usefulness in context of water projects, was tested through empirical part of the study.

3. Survey and results

Total number of 31 water infrastructure projects managers answer the questionnaire on usage and usefulness of MTTs. They were gathered based on snowball sampling, with the first 10 gathered within national government agency for water management. They were asked to fill the questionnaire up and distribute it to the people they thought were the most competent to answer. By sampling like this, the survey was also answered by the project managers working in utility companies, contractors and consultants as well. Most of the respondents were male (65%), between 31 and 40 years old (45%), owning university degree (84%), and had construction educational background (72%). Averagely,

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respondents had 12 years of working experience, in which they worked on 6 projects. Average managed project lasted for 3 years and had financial value of 16.7 billion EUR.

Respondents were asked if they think that used methodologies, standards and MTTs on water projects are adequate in the sense of fulfilment of needs of water sector. Detailed results on this may be found in [13]. Then, respondents were given a list created through literature review (Chapter 2) in which they were supposed to check what they use and grade their usefulness/efficiency on Likert scale from 1 to 5 (where 1 = extremely not useful; 2 = not useful; 3 = nor not useful, nor useful; 4 = useful; 5 = extremely useful). Results were then divided onto three groups of methodologies, standards and MTTs: most often used (used by 13 respondents and more), frequently used (used by 5 to 12 respondents), rarely used (used by 4 respondents and less). The results are presented in Table 1. These tables combine data on M – mean grade of usefulness and frequency *f(n)* – number of units in the sample using a given element. Detailed additional statistics may be found in [13].

Table 1. Perceived usefulness of used methodologies, standards, methods, tools and techniques

Most often used methodologies, standards and MTTs	M	*f (n)*	Frequently used methodologies, standards and MTTs	M	*f (n)*	Rarely used methodologies, standards and MTTs	M	*f (n)*
Integrated groupware (e-mail, collaborative tools, shared access to web portals, etc.)	4.39	31	Other decision-making techniques and tools	4.14	7	Agile board	4.50	2
Lessons learned	4.38	13	Team building activities	4.00	10	Decision trees	4.50	2
MS Excel	4.29	31	Decision analysis - DA	4.00	6	“In house” risk assessment tools	4.00	4
Cost benefit analysis – CBA	4.17	18	Sensitivity analysis - SA	4.00	5	Trend and variation analysis	4.00	3
Reporting system	4.05	22	Communication plan	3.91	11	Earned value management - EVM	4.00	2
Oracle Primavera	4.00	16	“In house” project management tools	3.91	11	Critical chain method - CCM	4.00	1
Groupware (e-mail only)	3.94	18	Voice over internet protocol (e.g. Skype)	3.91	11	Delphi method	4.00	1
Gantt bar charts	3.93	27	Project management software developed “in house”	3.86	7	Resource leveling	4.00	1
Risk assessment	3.92	13	Work breakdown structure - WBS	3.86	7	Other risk assessment tools and techniques	3.75	4
Progress meetings	3.90	31	Other project management tools	3.83	6	“What-if“ scenario analysis – Cause and effect diagrams	3.67	3
Cash flow analysis	3.90	20	Microsoft Project	3.75	8	PMBOK® (Project Management Body of Knowledge)	3.50	4
“In house” communication and reporting system	3.89	18	Critical path method – CPM	3.75	8	SAP	3.50	2
Checklist analysis	3.87	23	Other information communication technology (ICT) support tools	3.73	11	Monte Carlo simulation	3.50	2
Progress reports	3.86	29	Life-cycle cost analysis (LCC)	3.71	7	Reliability analysis	3.50	2
PM methodology developed “in house”	3.74	19	Video conferencing	3.71	7	Other project management software	3.33	3
Trend diagrams/ S curves	3.71	14	Other project management methodologies	3.70	10	Probability and effect matrix	3.33	3
Project goals charter	3.67	15	Strengths, weaknesses, opportunities and threats analysis – SWOT	3.60	10	ISO 21500:2012 - Guidance on project management	3.00	3
			Project evaluation and review technique – PERT	3.60	5	Stakeholder analysis	3.00	3

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Flow diagrams	3.60	5	Fault tree analysis (FTA)	3.00	2
Probability analysis	3.57	7	Hazard and operability studies (HAZOP)	2.50	2
"In house" decision-making techniques and tools	3.56	9	Hazard analysis (HAZAN)	2.50	2
ICB (International Competence Baseline)	3.50	6	Agile project management methodologies	1.00	1
Communities of practice enabling tools (professional forums etc.)	3.45	11			
Organizational breakdown structure - OBS	3.40	5			
Precedence diagram method - PDM	3.33	9			
Risk register	2.83	6			

4. Discussion

Conducted survey revealed interesting results. Based on respondents' answers in the first part of the survey it was stated that 84% of respondents do not consider methodologies, standards, and MTTs used in managing water projects adequate to fulfil needs of water sector. Even 94% of respondents think that certain problems in managing water projects may be minimized by the usage of more adequate methodologies, standards, or MTTs than the ones being used. In other words, most of the examined project managers think that there is an evident gap between methodologies, standards and MTTs being used and those that would be of real help when dealing with problems on projects. The possible reasons for this gap may be found in inadequate education on maximization of possibilities' usage that those tools may provide, in project procedures that do not cope with realistic situation on projects (gap between theory and praxes), psychological or time-constraining reluctance in learning, developing, testing or accepting new solutions, missing of new and creative solutions that would be custom-made and combine benefits of old solutions with an answer to new needs, etc. These findings and possible causes lying beneath them may be of great significance in conducting a future research on the field.

All respondents use integrated groupware, MS Excel and progress meetings, which is to certain extant similar with results of [14], who, among others, found progress reports and PM software used by all respondents in their research. Thereby, the average grade of usefulness of the meetings is 3.90, MS Excel 4.29, and integrated groupware 4.39. Authors believe that these figures are not as big as they could be compared to the wide usage of those methods. What can be done in order to increase them is to adopt principals of meeting management, maximize possibilities of MS Excel by enhancing the level of users' knowledge, and explore further possibilities of cloud management or multidimensional decision-making investment approach on web-based project management solutions in general [15]. In addition, project managers most often use cost benefit analyses and project goals charters, which is not surprising, since those elements are often mandatory when applying project for some sort of outer financing models, such as those provided by the European Union or World Bank. Water projects are of large financial, time and complexity nature, so state usually cannot fund them completely. Following application process for funds requires usage of these and similar tools, making of risk assessments, and regular reporting.

Reporting on project progress and project issues is immanent to any construction project, especially the complex infrastructural ones, with a large number of stakeholders that all require precise information on timely manner. Reporting systems and progress reports are therefore a must have element, but could strive for improvements, due to the comparison of their usage and grades of their usefulness. Also, when having in mind purpose of reporting systems, a parallel with rather poor usage of communication plans and extremely poor usage of stakeholder analysis must be drown. This finding indicates the possibility that project managers in Croatia adopt those tools that are on some level (e.g. state, funding, company) mandatory, without maximization of the purpose and objectives of their usage. Only 9.7% of respondents use stakeholder analysis (which among other objectives, has a cause to detect who on project needs what kind of information in order to engage their influence and underline what is important to them – i.e. to detect effective communication strategy towards different stakeholders, which can then be transmitted in more details through communication plan and integrated as a part of reporting system on a project).

The similar phenomenon may be seen in usage of Gantt charts and S curves - they still remain a traditional tool when on area of project management. However, authors suspect an inadequate usage of their possibilities, especially because work breakdown structure (which should precede a creation of a Gantt chart) or critical path method (which is basically a logic behind a Gantt chart as such) is rather modestly used. Their possibilities may be seen in [16], who found out that S-curve', 'forecasting techniques', 'cost control software products' and 'Work Breakdown Structure' are the popular tools and techniques used for cost control in megaprojects.

When considering modestly usage, relatively small number of respondents in the first group (13) use lessons learned technique, which has an extremely high grade of usefulness. This may stress the need of establishing Project Management Offices within companies that will be in charge for data collection, data analysis and recommendations' distribution within project management procedures, methodologies, tools and project management environment overall.

Managing project environment is quite neglected in general. Decision trees, already mentioned stakeholder analyses, "what-if" scenario analysis, SWOT analysis and risk management tools are rarely used. These indicates that project managers do not perceive possible outcomes of their decisions and outer influences on their projects on adequate manner. When it comes to risk management, similar results may be found in [17], whose study in Australian construction sector provided evidence that many of the tools promoted by the risk standards/associations do not seem to reflect current project manager practice.

When making decisions, an interesting information is the one of high grading of „other decision making techniques and tools". Out of all decision-making techniques and tools that were offered to choose from, respondents graded the "others" category the highest. This may be one more evidence on the need of development of traditional decision-making tools.

When it comes to project management software, respondents most frequently use MS Excel and Primavera, often use MS Project also, and are less keen to usage of other IT tools.

Speaking of project management methodologies and standards, respondents mostly use those developed "in house". They often use ICB, and rarely PMBOK or ISO Guidance on Project Management. No one uses other methodologies (PRINCE, PRINCE 2, P2M/KPM, etc.). Still, 19% of respondents that use ICB as the most widespread methodology is a relatively small figure, regarding the impact ICB has on project success [18].

What can be seen in overall is that relatively small number of project management methodologies, standards and MTTs are being used on adequate manner. The reason staying behind this may be found in the belief of 84% of respondents do not consider methodologies, standards and MTTs used in managing water projects adequate to fulfil needs of the sector. In other words, if used project management solutions would concentrate on the things that really do make difference on projects, it would be reasonable to expect that usage and usefulness of those solutions would contribute to more competent project management, as well as more successful project outcomes. For instance, traditional tools such as Gantt charts, S curves, project goals charters and cash flow analysis do not have high grades in sense of usefulness, as authors had expected. However, a large number of respondents use them, possibly due to habits or official project procedures. This suggests that there is an area of contribution to development of useful, more custom based tools for managing projects, which could overcome disadvantages of existing implemented solutions.

Limitations of this study are few. First, this study has been made within a national context and on one type of infrastructural projects. Nevertheless, recommendations drawn out of it may be useful for regionally, mentality and industrially close countries. Although not much optimistic, the results of this research should not be run away from. These results are rough presentation of reality of construction project management in Croatia, where project management has relatively recently been legally recognized as an official role in construction on the one hand, and where construction companies mostly strive to survive on the market, on the other hand. By neglecting project management as such and labelling it as “one more problem to deal with within company”, construction practitioners often omit the fact that project management is not the problem, but the solution to existing problems. As stated by [19] when referring to project management situation in India - construction industry lacks a structure or pattern, which can be provided by the tools such as project management. This is a general conclusion that may be extracted and used regardless the research limitations. Further, regardless the limitation of this study, the idea behind this research as well as its results may be served as a pilot study in building a larger platform for conducting analogous or similar research on the field, whether in multinational or multisector sense, or both.

5. Conclusion

This study investigated usage and perceived usefulness of project management MTTs in infrastructure projects in the Republic of Croatia, on an example of projects from water sector. The results showed an existing gap between used and useful/efficient project management MTTs. Further research may be undertaken to discover reasons standing behind this gap and/or to build up a research platform combining several countries and types of construction projects.

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Validation of support tools for project management: Case of COPPMAN

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Abstract

Project managers have started to draw support from IT solutions to handle projects, which are more complex than before. Therefore, most of the companies have been generating solutions specific to their need in addition to available software for general use. Any designed product/software requires a testing process not only to check that it is correctly working (verification), but also to secure that it is successfully serving for the intended purpose (validation). To ensure validity, new trend in software development has become early interaction of the possible users of the software to the development process to improve product quality. Early evaluations of the users provide detailed probing of the need that supports structuring the design, whereas latter evaluations serve as behavioral analysis of the developed software. Thus, user interaction for validation of software can be integrated to design process life cycle at any level of the process with different purposes and detail of evaluation. This study exemplifies validation study of a construction project portfolio management tool (COPPMAN), which is developed to support construction companies in adopting project portfolio centered management perspectives. Within evaluation studies of COPPMAN, three professionals from a construction company were assigned as a focus group and their evaluations were obtained through discussions and interviews at three main levels of the development process as; needs analysis, model generation, and beta testing. The current study mainly handles the beta testing process, where actual utilization of COPPMAN was made with a sample of nine real construction projects of the company. Evaluations made during and at the end of the process appreciate the potential value of COPPMAN in decision-making at top management level with its expected benefits in "strategic planning", "business development", "organizational learning" and "knowledge management". Suggestions for improvement of COPPMAN were also obtained as possible considerations for the forthcoming update. This validation process acts as a successful complementary to other validation testing processes undertaken in the development cycle (expert evaluation, pilot testing and usability testing) by providing a real environment(/in-house) evaluation as a trial of actual utilization of COPPMAN.

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Keywords: construction industry; decision support system; project portfolio management; software testing; validation.

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1. Introduction

Challenge with managing projects have been growing with the recent developments in project-based industries. As a respond to this need, various project management software have been generated to address common or specific needs of project managers. Specifically, this study handles the sample process undertaken to generate a software/tool for construction project portfolio management (COPPMAN). Responding to the need of customer, namely direct users of a software, has been the major issue in software development to propose a product to be efficiently used in the long term. Design quality should be ensured in every aspects of a product considering its appearance, feature set and the interaction scheme (/interface), all of which should be in the context and fit with the purpose to ensure features that are not only responsive to accomplish intended tasks but also fully comprehensible and easily achievable [1]. Once the need is identified, it can be structured through devise ways ending with different products in each. Since there has been lack of a standardized method for the development of software products, checking quality of the product is required, which makes software testing a main concern in software development [2]. Testing is mainly analysing the difference between the actual and the required/expected results with the product. This evaluation can be made through two major aims as "verifying" and "validating" a software program to ensure that it meets technical and functional requirements respectively [3]. Thus, the undertaken methodology would be the leading contributor to the followed design process and the launched product [4]. Therefore, the focus should be structuring the product in the best way (serving for its users) for ensuring a level of success and intended quality with the product [2]. Since software is to be designed as a response to a problem in practice, exploration of the problem in practice (/in its field) is required as well as continuous contact with its potential users in the course of design [5]. The main consideration should be devising the input from its users at early stages and throughout its development in addition to preserving capabilities with the technical support provided [6,7]. Therefore, an iterative design process where validation testing is integrated plays a crucial role in improvement of a software product [4,8]. In the light of the provided information, this study mainly demonstrates the validation process undertaken throughout development of COPPMAN. It was delivered in a granted research project with the aim of supporting construction companies in adoption of portfolio management principles. A practical tool can meet their current need for transforming the traditional project-focused management perspectives to portfolio-focused initiatives by supporting comprehensive evaluation and decision-making processes. Successful management of portfolios may enable construction companies to gain competitive advantage through effective management of multi-projects in the light of the intended strategy by consideration of available resources and capabilities. The following sections summarize the steps undertaken to make COPPMAN serve for the intended purpose.

2. Validation in development of COPPMAN

Validation has been a continuous concern in each main step in the followed methodology for development of COPPMAN (Fig. 1). Following identification of the need, model as laying the foundations was generated as a response to this need and the software was generated in sprints ending up with two main versions as the "alpha" and "beta" versions that provide evaluation with different aims. "Alpha version" provides a more "feature functionality" oriented representation of the solution to ensure tuning in the design while "beta version" represents the "complete product functionality" as the most improved and ready-to-use version [9]. Each validation process provided assessment of the current development and the considerations required in the following step as the main drivers of the construction of COPPMAN. Main support has been drawn from the "focus group" consisting of three professionals from a construction company as supervisors of the overall process where additional evaluations were provided from other construction professionals in different stages to ensure triangulation to eliminate problems with existence, generality and quantification of the solution [5].

2.1. Needs analysis

"Focus group" study has been a successful method in generation of the preliminary concepts in the very early stages of a design project as the evaluations obtained from its representative users [4]. Thus, evaluation of the focus group was obtained in needs analysis to enable early and continuous feedback on development of the tool. Face-to-face interview with the focus group provided in depth investigation of the need in its field in addition to the general requirements identified through literature review. Literature review provided identification of the need in a more "project portfolio management (PPM)" oriented fashion in terms of the main principles and the tools available while interview reformed the need to be structured with specific needs of construction industry through data obtained as attitudes, behaviours and opinions for setting out the requirements. Investigation was focused mainly on their PPM perspective and current practices, limitations/rooms for improvement, details of required PPM system/framework and potential functions of a PPM tool. As a result of this dual investigation, the identified overall points of the need was validated by focus group where they ranked the complete list of the initial requirements as notable points to be considered as follows (Table 1). This list may serve as original considerations in generation of any study that may be addressing portfolio management initiatives in the construction industry while reinforcing the remark on its need in the industry. The list underlines the need of a "dynamic", "intelligent" and "visual" tool that would integrate "knowledge", "risk" and "strategic" management processes while addressing "resource" issues and taking into consideration "dependencies" between projects.

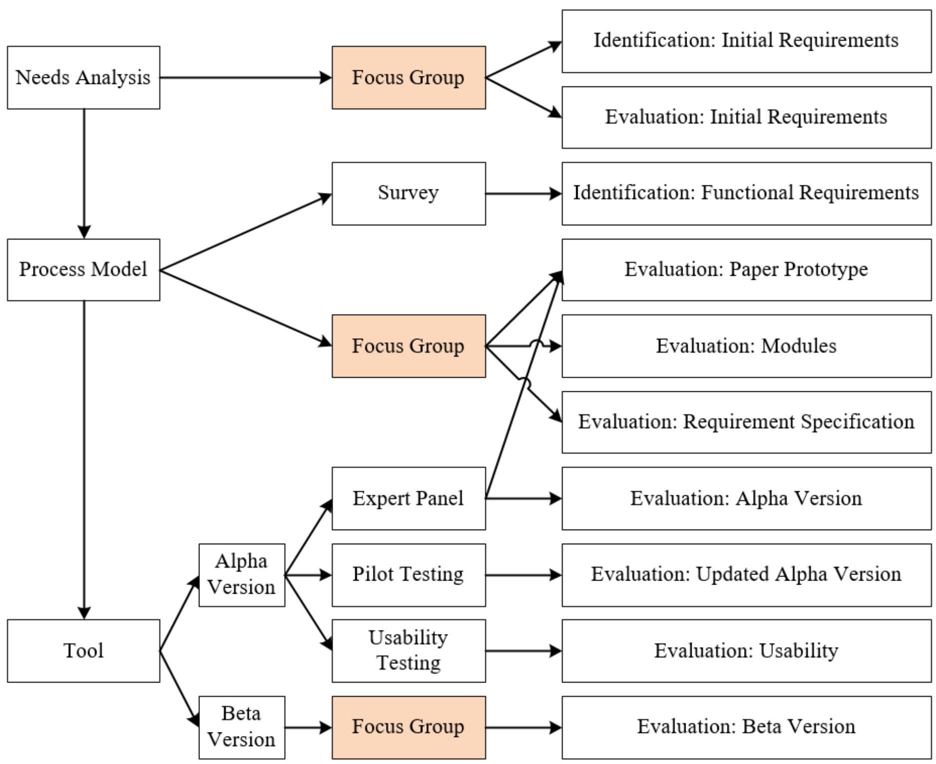

Fig. 1. Validation processes within methodology.

2.2. Model

The findings of needs analysis motivated/directed the research team to structure a "process model" that would encapsulate these through generation of the conceptual model, initial definition of its elements and a supportive algorithm that establishes the links between these elements within the process model. Data collected through a questionnaire survey, which was replied by 108 Turkish company professionals acting in the international market, supported the decisions and functional data to be used in algorithm of the tool as default figures. The identified system and its elements were materialized and improved through generating a "paper prototype" as complete depiction of the model. This numerical exemplification of the system by a hypothetical case (with 25 projects) was evaluated by the focus group and its potential success in responding to identified need was appreciated. Following that, the structured system was elaborated by the research team under five main "modules" handling different groups of the requirements each of which are acting as a building block of the overall system:

- System management module: provides the ability to identify/update company/industry specific concerns/requirements/preferences (e.g., editing default figures and ready-to-use inputs, establishing user management system, i.e. access and authorization issues, etc.).
- Knowledge management module: handles all project information and provides their utilization in the analysis through different data retrieval options and statistical data while supporting corporate learning as well (e.g., issues with post project appraisal, lessons learned, predictions, learning potentials, similar projects, etc.).
- Risk assessment module: enables project level analysis and presents portfolio level risk by integrating project dependencies (e.g., utilizing customizable project risk evaluation forms and investigating evaluation histories).
- Strategic assessment module: enables project level analysis and strategic prioritization at portfolio level (includes similar process with risk assessment module).
- Portfolio analysis module: establishes portfolios, supports decision-making through warnings (where resource sharing issues are also handled) and visualization by project/portfolio level measures/properties.

Table 1. Importance of initial requirements.

Requirement	Rating*
The established system needs to be IT supported.	7.00
Portfolio management tool for construction projects should support strategic choices.	7.00
Portfolio management tool for construction projects should support resource allocation decisions.	7.00
Portfolio management tool for construction projects should support balancing the projects and resources/capabilities.	7.00
Portfolio management tool for construction projects should incorporate past project data into portfolio analysis.	7.00
Portfolio management tool for construction projects should incorporate risk assessment into portfolio analysis.	7.00
Portfolio management tool for construction projects should handle dependencies between projects.	6.67
Portfolio management tool for construction projects should support project selection decisions.	6.67
Portfolio management tool for construction projects should enable visualization of portfolios.	6.67
Portfolio management tool for construction projects should be flexible and dynamic.	6.67
Portfolio management for construction projects should be intelligent and should provide advice/warnings about portfolio decisions.	6.67
Development of a portfolio management tool for construction organizations is required.	6.33
There is lack of an appropriate portfolio management framework and tools in construction companies.	6.33
Portfolio management process needs to be established/re-engineered	6.00

*Seven-Point Likert Scale ranging from “strongly disagree (1)” to “strongly agree (7)”

The feedback obtained by the focus group demonstrates that the proposed modules were successful to ensure the intended system with notable success in “knowledge management” and “portfolio analysis” modules through the evaluation provided as in Table 2.

Table 2. Success of modules of COPPMAN.

Modules of COPPMAN	Rating*
The structure of the “knowledge management module” is adequate for a construction project portfolio management tool.	6.33
The structure of the “portfolio analysis module” is adequate for a construction project portfolio management tool.	6.00
The structure of the “strategic assessment module” is adequate for a construction project portfolio management tool.	5.67
The structure of the “risk assessment module” is adequate for a construction project portfolio management tool.	5.33
The structure of the “system management module” is adequate for a construction project portfolio management tool.	5.00

*Seven-Point Likert Scale ranging from “strongly disagree (1)” to “strongly agree (7)”

The generated system and its modules based the decisions on “requirements specification”, which is the more definite and technically oriented form of the initial requirements, as translation of principles to features. Focus group also evaluated the structured requirements as in Table 3 where knowledge management centred requirements were identified as the most critical ones and substantial importance were obtained for the others as well.

Table 3. Importance of requirements.

Requirement	Rating*
Menu for entry of lessons learned, together with view and query options is an important feature	7.00
Calculation of dependencies between projects and visualization of dependencies with a dependency map is an important feature	7.00
Calculation and presentation of predictions for the on-going and potential projects through use of information of completed projects is an important feature	6.67
Tagging system for entry of lessons learned, including editing options for the tag tree and tag-based query is an important feature	6.67
Establishment of project similarity based search and calculation capabilities is an important feature	6.67
Menu for evaluation of risk and strategic fit factors, including editing of the factors and calculation of scores is an important feature	6.67
Establishment of filtering based search and calculation capabilities is an important feature	6.33
Calculation of portfolio attributes and depiction of results through tables, bubble diagrams and bar charts is an important feature	6.33
Menu for entry of different types of projects, together with view and query options is an important feature	6.33
Identification of different users in tool with different accessibility options to the tool menu/operations is an important feature	6.00
Automatic formation of the portfolio alternatives through addition of potential project combinations to on-going projects is an important feature	6.00
Establishment of an automatic warning system for current portfolios is an important feature	6.00
Identification of ready-to-use project inputs is an important feature	5.67
Development of a project representation to be used in visualizations is an important feature	5.67
Calculation and presentation of learning potentials for the on-going and potential projects is an important feature	5.33

*Seven-Point Likert Scale ranging from "strongly disagree (1)" to "strongly agree (7)"

2.3. Tool

The finalized requirements leaded generation of the first version (alpha version) of the tool, which was generated by a developer company through further discussions when required and the possibilities appeared with the advances of technology. The basic version was mainly capable of capturing and utilizing project knowledge and conducting portfolio analysis through considering interdependencies, risks and strategic objectives while enabling selection of the best portfolio by facilitating decision-making through warnings and visual representations of alternative scenarios in terms of project/portfolio level measures. Evaluations of the alpha version generally become "formative" by adding more to design and functions of the tool, so hold promise to make significant advance in the tool through revealing anticipated as well as unanticipated consequences. Whereas, evaluations of the beta version become more "summative" by focusing mainly on the product by assessing its value and utility outcomes [10]. Therefore, validation at both levels of the design with different participants was held to secure the improvement to be in line with the purpose by ensuring variability of the feedback obtained. Validations through "alpha testing" are generally done in a simulated use environment (development organization) while "beta testing" is the process of testing in the end-user site as the first "live operational test" of the software [3].

Regarding evaluation of the alpha version, an "expert panel" consisting of two academicians and two company professionals with no previous involvement in the study was set up for ensuring validity of the tool and the methodology undertaken. Expert panel provides investigation of reliability of the approach and the results while testing whether the important concepts in the domain are covered adequately or not [5]. The experts were selected considering their capabilities in both "portfolio management" and "information technologies" since expert evaluation provides an opportunity of external review considering the target user of the product by raising awareness in both usability heuristics and domain in question [4]. They were allowed to access and navigate within the tool where the sample case in prototype was analysed as the base model to reflect the "mental image" of the model. The panel provided a dual evaluation of the paper prototype (so the model) and the alpha version to benchmark the expected/intended purpose with the actual purpose. This process provided both "functional" and "operational" testing of COPPMAN through positive results obtained in questionnaires by open-ended questions and ratings on "completeness/coverage", "suitability/accuracy", "usefulness", "usability", "receptiveness", and "overall". This testing ended with an update in the alpha version addressing revision in its functionality as improvement in the visual and searching capabilities of the tool.

The new version was tested through "pilot testing" where the tool was directly used by two different company professionals with their own portfolio samples as the case studies consisting of hypothetical set of real projects under supervision of the research team. The pilot testing provided a transition between the current evaluations as expectations/feedbacks obtained according to presentation of the development and the evaluations that would be made by its direct utilization. The "pilot testing" acted as evaluation of the tool as well as validation of the initial test results and testing materials (i.e. questionnaires to be used in further testing). It provided "operational" and an implicit "usability" testing with extended list of usability centred attributes differently from expert panel study. This evaluation validated the current version of the tool as the first trial of its utilization and its readiness to further testing. Obtained feedback provided final tuning in some of the sections as the final update in terms of aesthetic changes in some buttons, tables, etc.

As a complementary to these processes, testing with major focus on behavioural analysis of the tool was required to assess its practicality, capability and possible benefits. The forthcoming testing was more focused on its usability where the success of the tool considering its interaction with its user was tested in laboratory setting (Human-Computer Interaction Research and Application Laboratory, Middle East Technical University (METU)). "Usability testing" provides consideration of several aspects such as how easily the users learn the system, how efficiently they use the system once they learn how to use it, and how much they are pleasant to use it. The criticality and frequency of errors during the testing process constitute supportive data for consideration of overall usability and possible areas of further improvement in design. Six participants, research assistants from Civil Engineering Department METU, as representative users were tested through "14" pre-defined realistic task scenarios ("pieces of real work") for deeply monitoring the trial of its utilization [11]. Advances of eye-tracking technology and the analysis software provide analysis of the performance data through analysing the micro-level behaviours of the users that may be indicator of the problems, which would not be detected otherwise [4]. Participants successfully undertook the scenarios with indication of minor problems due to its first use. It provided more interface-oriented diagnosis through analysis of both "performance data" (as task completion success rates, time on tasks/fixation durations, mouse click counts, visual outputs as heatmaps, gazeplots, clusters) and "preference data" (through questionnaires including open ended questions and ratings all addressing measures on ease of "use/efficiency", "effectiveness", "satisfaction", "consistency", "learnability", "user guidance", "overall", and some further measures on its "usefulness"). This testing appreciated the current flow of the process and design of the tool, thus ended with no critical update in the current version. Therefore, usability testing turned the latest alpha version to serve as the beta version as well, for its further testing in its real environment as trial of its actual utilization through beta testing.

3. Beta testing

As the last step of evaluation, "actual implementation" with the beta version of tool was made by the "focus group" in their company as the first implementation in the "real setting". The company professionals conducted analysis on the created "real set of portfolio" to evaluate the first real experience with COPPMAN.

3.1. The company

The company was selected due to its place in the international market and their current attempts in establishing portfolio management initiatives. It holds turnkey power generation projects as the Engineering, Procurement and Construction (EPC) contracting arm of a holding, which owns several companies that all serve for construction of power plants, refinery, cement, petro-chemical and gas plants, factories, high-rise buildings, water treatment plants and transmission lines, bridges and other infrastructural constructions including various energy investments. The power systems company undertakes power plant EPC contracts particularly in the gas combined cycle power plant arena and provides combined services of engineering, procurement, construction, commissioning, start-up, warranty and spare parts services for almost all types of power plants. Therefore, the company is the correct choice for beta testing with their broad range of projects in the international market, mainly in Middle East, Turkey, Africa and Commonwealth of Independent States (CIS). The same professionals (focus group) from the units of "business development", "business control and risk management", and "enterprise systems" participated in testing since their contribution was considered to be important due to their know-how in the issue and the development process of COPPMAN as well.

3.2. The case/portfolio

A sample portfolio was created including somewhat similar projects (i.e., "combined cycle power plant projects" in majority) to make the outputs of COPPMAN representative of typical considerations required in the analysis with minimum information entry. Five "completed project" information with five crucial "lessons learned" in these projects were entered together with two "on-going projects" and two "potential projects". Following establishment of the portfolio, the focus group followed typical analysis process in COPPMAN where they shared live feedback through their experience in each process in terms of sufficient/useful properties and further improvements:

- Data entry: included identification of project inputs and preferences as the initial setting for entry of project information and related lessons learned. This process revealed possible improvement in export/import capability for data transfer, extent and entry type of some captured information, and inclusion of more information as "free-text area for project notes", "project significance", "critical milestones", and "checkpoint" as integration of "change management" initiatives in addition to currently provided information (i.e., "general project information", "critical resources", "partnership information", "duration, financial, project dependency and technology information", "post project appraisal information" and "lessons learned").
- Data analysis: was focused on investigation of "supportive information", namely the data retrieved for "on-going" and "potential" projects based on information of "completed projects", assessment of "risk" and "strategic fit" for these projects based on the obtained information. The analysed information as "similar projects", retrieved "lessons learned", obtained "predictions" and "learning potentials" together with the "retrieval options" were found successful for benchmarking the project at hand prior to analysis of "risk" and "strategy". Final tuning in some calculations was advised as inclusion of more "project attributes" or provision of more flexibility in calculation options.
- Data output: provided analysis of the overall portfolio alternatives, investigation of portfolio and project specific outputs, and performing portfolio selection accordingly. Visual/numerical outputs and the warnings were found helpful in supporting decision maker; however, integration of more flexible "reporting mechanism" addressing unique needs of different users with special focus on some specific points was advised for increasing the success and usefulness of the outputs. Additionally, some minor aesthetic changes in graphs were advised for making some points more visible and attractive for the user where some expressions were to be improved. Flexibility was advised to be increased in some of the calculations, in addition to corrections needed considering outlier data, which further required identification of "exceptional projects" and adjustment in calculations and presented "warnings". As a final remark on analysis of portfolios, integration of a dashboard as "geographic map" that unifies all project figures and representative information on the filtered projects was advised to be more beneficial to "see the big picture" and analyse the overall portfolio or specific portfolio alternatives. Regarding portfolio selection, identification of "strategic hold points" to automate elimination of portfolios that would not be in the stated limits was suggested to be useful.

3.3. Findings

In addition to live feedback through utilization of the sample case, focus group provided an overall evaluation on COPPMAN at the end of the analysis, which are provided below in main sections of "strengths", "shortcomings/improvements", "possible benefits", "possible barriers", and "overall rating":

- Strengths: COPPMAN has the potential to unify different departments on the same portal since it encapsulates several systems required for portfolio analysis and builds a link to projects while establishing a bridge between past and current projects. Knowledge retrieval mechanisms with possibility of successful benchmarking and numerical forecasting ability (i.e. "predictions") constitute the main strengths of COPPMAN. Especially integration of lesson learned management system (which was generated and released as a separate tool (LinCTool) in a complementary study held by Eken et al. [12] with its potential to be used irrespective of portfolio management issues) is quite successful within the system. Support of numerical outputs in addition to visualization abilities are also helpful in addition to warnings as reminder of the points to be noticed.
- Shortcomings/improvements: may be the considerations on the points identified throughout its use as improvements regarding "extent of information", "addition of context", "eased information entry", "flexibility in calculations", and "reporting abilities" (which are outlined in the previous section "the case/portfolio").
- Possible benefits: COPPMAN would be important at holding level and support decision-making for companies working with different type of projects in their portfolio. It can also be valuable for the companies that are working with similar kind of projects in their portfolios due to possible benefits in facilitation of "strategic planning", "business development", "organizational learning" and "knowledge management". It would help to present the company know-how and experience in a single visual platform, which may be highly advantageous during potential project/portfolio selection with the supported analysis.
- Possible barriers: Strong coordination between different divisions is needed since they would work on the same platform where data collection and refining issues would be under control of a unique department/professional, which may be possible barrier to fully utilization of COPPMAN.
- Overall rating: In addition to the preference data obtained through open-ended questions, an overall rating was obtained as presented in Table 4. The focus group was satisfied with overall "implementation" process and COPPMAN was evaluated as "effective" in portfolio management and appreciated for its "support in decision-making" with its adequate "features/components" and "user-friendly" structure. The tool is stated to be "implementable" in the company of investigation and also in similar construction companies through its appreciated abilities of "better visualization of the portfolios", "effective reporting and documentation" and its support in "strategic evaluation", "selection of the right projects", "portfolio risk evaluation", and "short term and long term planning". Regarding the additional checklist for "possible benefits" of utilization of COPPMAN, all the respondents achieved consensus on the benefits in "strategic planning and strategic achievement", "project selection and portfolio optimization", "knowledge management and organizational learning", and improvements in "communication, documentation and reporting" where further possible benefits were selected as advances in "risk minimization" and "long term profitability" by one respondent.

3.4. Result

Real application addressed "operational" testing (i.e. usefulness) of the tool for measuring its potential benefits as well as further evaluation of its "usability". Direct utilization of the tool revealed some additional considerations that might be structured upon current capabilities provided with the help of technology. At the end of beta testing the current version of the tool was appreciated to be sufficient to serve for the expected purpose with its potential benefits for construction companies. In the light of the feedback obtained, a final update on COPPMAN has been performed as the update on the accepted version based on improvements in the current functionality of the tool. The update addressed mainly a general improvement in the structure of COPPMAN, integration of "geographic map" and improvement of "reporting" abilities while facilitating the information control through a common "project layer" and increasing flexibility in "calculations".

Table 4. Overall evaluation on COPPMAN.

Statement	Rating*
COPPMAN tool facilitates decision-making for managers.	7.00
We are satisfied with the features/components of COPPMAN tool.	6.33
COPPMAN tool supports effective reporting and documentation.	6.33
COPPMAN tool facilitates visualization of the portfolios.	6.33
COPPMAN tool provides an effective portfolio management.	6.00
COPPMAN tool facilitates strategic evaluation of the portfolio.	6.00
COPPMAN tool eases selection of the right projects.	6.00
We are satisfied with the COPPMAN implementation.	5.67
COPPMAN tool is useful for portfolio risk evaluation.	5.67
COPPMAN tool provides support for short and long term planning.	5.67
COPPMAN tool is user-friendly.	5.67
COPPMAN tool would be implementable in similar construction organizations.	5.67
COPPMAN tool provides adequate warnings regarding the portfolios.	5.33
COPPMAN tool would be implementable in our organization.	5.00
COPPMAN tool is useful for organizational learning.	4.67
COPPMAN tool does not require extra burden (additional cost / workload or legal issues) for implementation.	4.00

*Seven-Point Likert Scale ranging from "strongly disagree (1)" to "strongly agree (7)"

4. Discussion and conclusion

Phased validation of COPPMAN maintained the complete support in development of the tool to make the process be in a more user oriented fashion. Early integration of the potential users led reshaping the design through feedback obtained on the materialized sections of the product, which provided the direct demonstration of the status and structuring its further development properly. Needs analysis provided setting up the context and crucial points, model development enabled formalization of concepts in a framework as features of the system, and evaluations on tool provided better demonstration and revealing further points to be considered through the opportunities provided with technology. Especially, the beta testing process served for evaluation of direct experience of the user with COPPMAN, appreciation of its possible benefits and points to be considered in a possible update. This methodology has provided a way for generation of a software that would be applicable by its users in the light of the first signals obtained on its potential success. However, actual benefits are to be only observed in case of its adoption and utilization by construction companies. The main contribution of this study lies in framing the need by joint effort obtained through literature and field studies, which can be deemed as an essential start required for any research in this field. Overall methodology undertaken in this study exemplifies a user-oriented software development process whose findings may serve for further studies undertaken in construction project portfolio management literature and for PPM studies in other project-based industries as well.

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Value Methodology in the Real Estate Practice

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Abstract

Value Methodology (VM) is a management consultancy methodology that dates back 60 years. According to its definition, value is the ratio of function and resources. VM is a complex decision-support procedure that takes the consumer's need as a starting point and, in order to reach the technical-economic optimum, analyses and shapes the relationships between the functions and costs of a product in a constructively critical manner, as part of team work, in the course of a closely monitored process to create a more favorable value. VM is widely used in various industries, including the construction industry. The methodology is also successfully applied in production processes in Hungary. However, it is striking that the use of VM is not common in segments related to real estate consultancy.

This article examines the possible role of VM in the real estate practice, using the method of requesting expert opinion in a training program. The survey clearly shows that both the whole of the methodology and certain of its elements could be included in the everyday practice of real estate experts.

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Keywords: Value Methodology, Value Engineering, Real Estate, Real Estate Valuation

1. Introduction

A special course brought together representatives of two consultancy segments with very similar names. These two segments are Real Estate Valuation and Value Methodology (VM). Both fields date back decades, adhere to strict rules and standards, and have prestigious professional organizations that cultivate their experts. It is difficult, however, to find a professional link between the consultancy segments, as the overlap between the methodologies used is very small. VM uses the opinions of real estate consultants and their results as data input, while the literature review shows that real estate consultants have not used the diverse methodological tools of VM so far.

The goal of the current survey is to examine, from the perspective of the real estate consultancy segment, in what way the methodology of VM could improve the daily work of real estate professionals and make the results of their analyses and valuations more accurate. The question is, "In which fields and in which activities it is possible and practical to apply VM?" This study is structured as follows: Chapter 2 presents the basics of Value Methodology and its application in the construction industry; Chapter 3 describes the objective, methodology and circumstances of the research; Chapter 4 contains the results and their analysis, while the last chapter explains the conclusions drawn and the recommendations put forward based on the research.

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2. About Value Methodology

The story of VM started after World War II, at the American corporation, General Electric. The first publication was prepared by Miles [1], project manager at General Electric, and was later followed by his definitive book [2]. Miles laid the foundations of Value Methodology. He claims that the options available to industrial designers when further developing products are strongly limited if they take the current state of the product as the starting point. According to the VM approach, designers should first examine the field of use for the product and exhaustively explore the needs of users. They should subsequently define the functionalities of the product and how the product has to meet certain needs. Only then should they search for solutions for the implementation of the functions. In general practice, developments thought through in this manner can achieve a cost reduction of around 10-25%. The method was found so effective in America that it has been applied on a mandatory basis in the arms industry since 1964, in environmental protection since 1978 and in public procurements as a general obligation since 1996 [3]. Value Methodology is a design approach, a systematic development tool and a decision-support procedure. Instead of seeking only to find the cheaper or better solution, it meets a need (benefits) at minimum cost (sacrifice). With a solution that meets this dual requirement, it is possible to create a product or service that is suitable from the point of view of the consumer, the user, i.e. satisfy the client.

According to its definition, value is the ratio of function and resources. VM is a complex decision-support procedure that takes the consumer's need as a starting point and, in order to reach the technical-economic optimum, analyses and shapes the relationships between the functions and costs of a product in a constructively critical manner, as part of team work in the course of a closely monitored process to create a more favorable value [4]. VM is widely used in various industries, including the construction industry.

VM use in the construction industry is commonplace [5]. Although construction projects can be designed very well, "hard thinking" does not necessarily work in this case, as various stakeholders may have different goals [6, 7]. The main reason why the use of VM in the construction industry is typically problematic is either that its user does not know VM well enough, or their experience as a facilitator in Value Methodology is insufficient. An additional reason is that, in contrast with production, products in the construction industry are a lot more complex and have many more variables or elements of chance [8]. The decision-making systems applied in VM must be adjusted to the special features of the construction industry [9]. In certain countries and areas, the application of VM is hindered for special reasons. In Hong Kong, it is the high plot price that VM cannot control, while the favoring of friends and family in tendering procedures is also an obstacle [10]; according to a study in South Africa, the failure of its application is caused by the lack of communication [11], while in Nigeria, the stakeholders of the construction market reject the new method [12]. Elsewhere, Value Methodology is used as the fulfilment of a formal obligation, but does not result in considerable benefit due to the low effort exerted by experts [13, 14]. However, in countries where the application of VM is not mandatory, market actors call for a government measure to make the methodology obligatory as part of the local construction process [15, 16, 17].

Overall, the literature reports on favorable experiences in the application of Value Methodology in the construction industry. Various studies claim that using VM, savings of 5-10% can be achieved, while user satisfaction can also be significantly increased [18, 19]. It is important for Value Methodology to be introduced in the project as soon as possible, since its application in the early stages results in greater benefits [4]. Researchers see an opportunity for further development in the automation of VM; using artificial intelligence, Value Methodology can provide truly efficient assistance in the entire implementation process [4, 20].

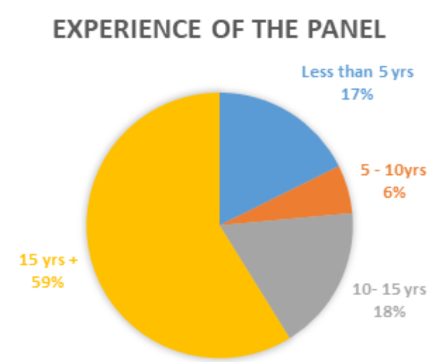
The literature does not discuss the use of VM in the field of real estate. In this topic, the RICS guide, which summarizes the concept of VM for professionals exercising activities in the real estate sector, is unique for now [21].

3. The Research

The series of master courses offered by the Budapest office of Grant Thornton provided a great opportunity for carrying out the research. The master course was created to summarize the existing national and international knowledge, practice and information in connection with valuation, and help the participants in the master course acquire this organized knowledge, as well as make this knowledge available to the broader professional public. Each session of the master course focuses on one selected, relevant topic, typically in the form of a 3-day intensive and interactive series of lectures. The course is generally taught in small groups of 15-20 people, and ends with the preparation of a final "thesis", which contains the conclusion of the joint professional opinion of the participants. The topics for the master course events held previously included the valuation of stigmatized property, the valuation of municipal property and the impact of the Big Data era on valuations. The topic of the 8th master course was the detailed discussion of the previously described problem. The invited students were professionals in the field of real estate consultancy with great theoretical and practical experience. The course entitled "Value Methodology in the Field of Real Estate" was held at Budapest University of Technology between 14 and 17 February 2019. The course was instructed by Lucie Parrot, a Canadian professional with great experience in Value Methodology. Over the course the three days, the participants obtained an overview of Value Methodology and its application in the construction industry and learned to use the core techniques of Value Methodology themselves as part of a minor exercise. The participants of the course learned about the technique and followed the entire Value Methodology process as part of a case study together. After the preparations, the participants discussed the possible cases where VM could be applied in the field of real estate valuation as part of group work, and put forward various relevant recommendations during a "Barnstorming Section", recommendations which they also ranked in the assessment phase.

In the course of the research, we took advantage of the fact that participants formed their own opinions on the applicability of VM at the end of the intensive learning process. At the beginning of the course, we asked them about their attitudes toward VM, so we had the opportunity to compare the initial and post-course views of the students by asking the same questions at the end of their learning process.

A total of 17 experts participated in the course, and, thereby, the research. The distribution of their experience in the real estate market is illustrated in Figure 1:



1. *Figure: The distribution of expert experience within the panel*

As can be seen, the participants had great experience; their average experience in the real estate market was 14.5 years.

The questions asked at the end of the course were divided into four main functional groups:

- Respondents' attitude toward VM
- Applicability of individual methods of VM in the field of real estate valuation
- The application of VM in certain priority areas of real estate valuation
- The application of VM in the Hungarian construction industry.

In the course of the research, we asked respondents to answer a total of 18 questions. We requested and registered the answers using multiple-choice questions and a free software called "kahoot" (www.kahoot.com). The respondents were not able to see the individual or aggregated responses from the group members after answering the individual questions, only after the survey had been closed (and even then, they did not see the individual responses). Each question was multiple-choice with four possible answers. We assigned the values of 0, 0.333, 0.666 and 1 to each option in ascending order, using the aggregate amount of which we determined the joint opinion of the respondents. The lowest possible value was therefore 0, while the highest was 17, according to the number of participants, where 0 is the lowest and 17 the highest support.

4. The Results

The course participants demonstrated a positive attitude prior to the course. Although their knowledge of VM was strongly limited (6.920), they found the role of "soft thinking" important in real estate consultancy (8.809). This value increased after the course, the opinion grew stronger (11.330).

The applicability of individual VM methods was found to be good and was generally supported by the experts. Table 1 shows the answers in order of support.

Question No.	VM method to employ in RE Consultancy	Compound answer value
R4	Usage the Creativity Phase	12.661
R5	Usage outside expert group	10.994
R7	Usage pre-decided time frame	10.994
R6	Usage the systematic process flow	9.661
R3	Usage the Function Analysis	9.659

1. *Table: Applicability of individual VM methods*

The second main set of questions was about the applicability of VM as a full methodology in certain real estate consultancy activities. Table 2 also shows the possible areas of expertise (together with their support) in order of support of the panel.

Question No.	VM usage for	Compound answer value
U4	Feasibility Study	14.662
U5	Hedonic approach in RE valuation	14.662
U2	Residual Valuation	13.327
U1	HBU analysis in RE practice	13.326
U3	Estimation of the obsolescence of a property	12.993
U6	Stigmatized properties analysis in RE valuation	12.993
U7	DCF analysis in RE valuation	10.662

2. *Table: The possible areas of expertise*

The course participants also expressed their overall opinions on the application of VM in the Hungarian construction industry. In principle, the respondents endorse the widest possible use (11.661), but do not find the obligatory introduction of VM in the near future feasible.

In the course of analyzing the results, we were looking for statistical connections between the respondents' careers, previous experience regarding VM and responses given to the individual sets of questions. We did not find any correlation between previous experience and the applicability of VM in the Hungarian construction industry; there was a weak correlation (R=0.398) between expert experience and the opinion on the applicability of VM methods. On the other hand, the respondents assessed matters in a consistent manner; a strong regression relationship was detected between the average of answers given to the two main sets of questions (R=0.548).

5. Discussion

Value Methodology is a discipline whose methodology can be used in various fields [22]. Real estate consultancy is also a long-established, well-regulated activity. Big Data and modern analytical methods supported by artificial intelligence have emerged in the field of modern real estate. Nevertheless, the human factor is still indispensable in the course of design and implementation [23]. The experts participating in the panel have significant experience, they consider the above statements as basic principles. They formed their judgment on the applicability of VM taking them into account. They find its introduction particularly useful in professional areas where the standard solutions are associated with subjective judgments (feasibility studies, hedonic method, residual valuation). This is why, out of the VM methodologies, the respondents placed the joint description of the community's experiences, the Creativity Phase first – since, instead of individual views, this approach (which is well defined by VM) incorporates the results of the work of a well-prepared and committed team into to otherwise fixed real estate consultancy process.

The given responses are consistent in the expert sample. Linking the applied research method, i.e. request for expert opinion, to prior training and group work could have clearly led to a collective commitment to the matter. This may result in an increase in support, but since there was no feedback on the results during the research, no deflecting effect occurred regarding the order. Since there are currently no experts who practice in both consultancy fields, combining the research with a training course was reasonable.

6. Conclusion

The survey confirmed the initial hypothesis that Value Methodology can be applied for the facilitation of real estate consultancy activities. Since real estate consultancy also requires a “soft” approach, certain VM solutions that use the same method could provide assistance in the performance of real estate activities with a methodology that allows for designing and monitoring. In certain fields of consultancy, particularly in the case of mass valuations, which require comprehensive analyses, or the field of feasibility studies, VM offers a new and well-established toolset to experts working in the field.

The research is intrinsically very limited; partly because members of the panel reflected on the circumstances in Hungary and gave their answers based on them, and partly because in the research, the transfer of information on VM took place only as part of a short, 3-day course. However, VM has not yet been used in the field of real estate consultancy (its application has not been described), so the results of the survey justify further research. The current survey is an initial study of the applicability of VM in real estate consultancy. Spreading the application of VM to a broader professional public in the fields specified in the research is only possible after the performance of additional practical case studies.

The incorporation of the Creativity Phase, which was placed first by experts, into the usual consultancy procedures is to be examined as a priority. In this regard, extending the current research to the establishment of a process model that meets the requirements of both disciplines examined is recommended.

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What are the Barriers and Drivers toward BIM Adoption in Nigeria?

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Abstract

The 'digitalization and collaboration' or Building Information Modelling (BIM) in the construction industry has been gaining momentum in the recent academic engagements. Despite its existence in many industries (i.e. publishing, retailing, financial and travel services) for over a decade, the construction industry is yet to catch up with them. This is due to several challenges whose existence are more dynamic and perhaps generic than static to various countries. The challenges are mostly defined, but their impacts are frequently varied with boundaries; and the same applied to drivers toward a successful BIM adoption. This study aims to establish barriers and drivers to adopting BIM across Nigerian construction industry professions for synchronization and collective engagements. Primary data was fetched from professional stakeholders (Architects, Engineers, Builders, Quantity Surveyors, Project Managers and Planners) using online structured questionnaire. A total of 68 valid responses were analyzed using descriptive statistics. The study reveals a significant improvement in awareness level with much better adoption rate; however, the utilization level remain very limited due to lack of clarity, knowledge and guide. Lack of expertise within organizations and within project team as well as lack of standardization and protocols (in descending order) were found as significant barriers to BIM adoption. On the other hand, availability of trained professionals to handle BIM tools, proof of cost savings by its adoption and the BIM software affordability (in descending order) were found as the significant drivers to achieving a quick and effective BIM adoption. Recommendations were made based on the study findings.

Keywords: adoption; barriers; BIM; construction; drivers; Nigeria

1. Introduction

Building Information Modelling (BIM) is the process of creating a digital model of a building or infrastructure facility. The fundamental idea behind BIM is to create and share the right information at the right time throughout the design, construction and operation of a building or facility, in order to improve efficiency and decision making (CIOB). This new paradigm shift in the construction industry is gaining high recognition both in the academic discuss (research) and the industry (application). However, its wide (universal) adoption is facing ordinary challenges but yet persistent within the industry and across the world. These challenges are more the same rather than different; although their significance and uniqueness vary with country. On the other hand, the drivers that facilitate its adoption have similar trend with the barriers.

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BIM is similar to other technologies or innovations, it comes with challenges and barriers while in adoption and implementation process [1,2]. Barnes and Davies [3] revealed the most perceived barriers against BIM adoption by organisations as issue of readiness, high cost of training, and cost of technology investment (hardware and software). This readiness could be the ability to agreeing to change (awareness driven) or technology and manpower readiness. Construction industry is widely known to be conventional and resistive to changes [4]; however, this new technological process has come to stay.

Eadie et al [5] worked on the identification of barriers to BIM adoption and their order of importance, this study revealed so much to the UK BIM adoption strategy and more importantly directing to the most significant barriers as to allow adopters pay more attention to them. However, solving one or more barriers without resolving all will not bring the end to challenges on BIM adoption [1]. Some studies from Nigeria reveal some barriers to adopting BIM [6,7], but not to common professionals or wide market (macro scale).

This study is aimed to fill the gap of differentiating by order of importance, the common barriers vis-a-vis to drivers toward BIM adoption to the stakeholders in Nigerian construction market. This will allow a unified action by policy makers and players in the industry to achieve a common goal.

2. Literature Review

BIM is amongst the most discussed subjects in the AEC and perhaps the most discussed area of development in the AEC process. There are huge development, research and effort to implementation of this new innovative process. Hjelseth [8] compiled five years publications (2007-2017) from Automation in Construction in the field of BIM, his statistics reveal high (>70%) concentration on interoperable technology perspective than collaborative processes. Thus, suggests more to awareness of the real understanding and how BIM influences AEC activities. On the other hand, some investigator believed that researchers have concentrated mostly on adoption and non-adopters, investigating the barriers and drivers, development of models and frameworks [9,10]; albeit there is irregularity in the adoption as well as the implementation across the globe and across different disciplines.

There are several investigations and study on BIM development and usage around the globe. McAuley et al [11] mapped the global overview of BIM adoption, Africa is the only living continent who does not have representation. Interestingly, lessons were set to learn at country levels, especially their respective adoption trends. Several countries around the world have being striving to preserve the digital shift, for example, USA, UK, Australia, Singapore, South Korea, Denmark, Russia and Finland to mentioned but a few are the front runners [11]. There are bodies that survey the BIM adoption and provide Noteworthy BIM Publications (NBPs) from many of these countries, so as to maintain guide and also keep track of the BIM progress. BIM Innovation Capability Programme (BICP) – Ireland; National BIM Reports by National Building Specifications – UK; NATSPEC – Australia; and SmartMarket Report by McGraw Hill Construction – USA are some of the bodies. For world-wide assessment of BIM adoption and its business value, McGraw Hill Construction remains the only source of NBPs [11,12].

In the recent academic discuss, there are several investigations on social aspect of BIM adoption, such as readiness, awareness, level of adoption, capabilities (stages) as well as barriers and driver toward the adoption and implementation [13]. Such efforts (by countries and organisations) played a significant role in revolutionising the adoption process [14]. Sequential studies conducted regarding the challenges faced while adopting BIM were found to be continuous, starting with [6], to [13,15 and 16].

Wang et al [6] also compiled and ranked some challenges faced by Mechanical, Electrical and Plumber (MEP) firms in Nigeria, lack of technical expertise on BIM tools utilisation, lack of awareness of BIM technology as well as high cost of investment on staff training, process change, software and hardware upgrade were the most critical barriers. While Onungwa et al [7] reveal lack of skilled personnel, lack of internet connectivity, and reluctance of other stake holders to use BIM, lack BIM object libraries and lack of awareness of the technology as the main barriers to BIM adoption. Albeit citing lack of adequate support or motivation from leaders and political office holders and lack of trained personnel who are abreast of the latest development in technology as the earlier identified challenges. They also lamented the BIM knowledge gap where most Architects learn on the job as no training is mostly offered.

In NBS report [17], barriers to BIM adoption are named under two umbrellas, internal (i.e. lack of training, expertise and funds to invest) and external (i.e. lack of client demand and lack of big projects that require BIM). The most recent compiled barriers by [13] were grouped into five categories, these include personal, legal, management, cost and technical for convenience in analysis [15]. There are twenty-two compiled BIM adoption barriers that were extracted from 62 publications. Table 1 of [15 p.768-770] presents the summary of the barriers; however, that does not necessarily apply to the entire professional fields, organisations and countries as common. For example, UK reported 18 barriers in their continuous BIM assessment survey [17 p.35], and these barriers are not exactly as those extracted by [15] or those in [6]. However, there are several similarities and common terms across the lists. For example, Khosrowshahi [18] reported many barriers to adopt BIM across UK and assert that the barriers are commonly on organisational readiness. Table 1 below summarises the compiled potential barriers to BIM adoption in Nigeria.

Table 1. Barriers to BIM adoption

S/No.	Barriers to BIM adoption	Reference
1	Lack of expertise within the organisations	[1,6,16,19,20,21,22,23]
2	Lack of expertise within the project Team	[6,16,22,23]
3	Lack of standardisation and protocols	[6,16,22,24]
4	Lack of collaboration among stakeholders	[6,16,24]
5	High Investment Cost	[20,25,26,27,28,29,30,31]
6	Legal issues around ownership, IP & PI insurance	[19,22,26,32,33,34,35,36,37,38]
7	Lack of client demand	[6,22,23,24,39]
8	Lack of infrastructure	[6]
9	Lack of government policy	[6]
10	Industry's Cultural resistance	[20,40,41,42,43]
11	Lack of additional project finance to support BIM	[19,22]
12	Resistance at operational level	[22]
13	Reluctance of team members to share information	[6,19,20,]
14	Return on Investment (ROI) issue	[25,31,43]

Lack of expertise, training and cost are consistently remaining amongst the major barriers to BIM adoption across some countries. Countries like UK [17,44,45,46,47], Malaysia [22] and Nigeria [6,7,48] are example of such. In the UK lack of expertise is attributed to the underperformance of the Higher Education Institutions (HEIs) with mostly low levels of engagement with the industry [49]. While in Nigeria, students are generally trained on 'file based collaboration' – 2D and 3D CAD and HEIs are not technically ready to offer BIM training at all [50].

Drivers to adopt innovation are simply the facilitators to adopt the new product or process [23]. The facilitators are the enablers, as resolving the barriers ease the innovation adoption, the same way the drivers support the adoption process. Potential drivers mostly fall under empowerment, leadership, and creative culture; and most barriers are interlinked with drivers. In most cases, removing a barrier is literally providing a motivator. For example, solving lack experts/trained personnel on BIM means providing training on BIM. Table 2 below summarises some potential drivers from previous studies.

Table 2. Drivers to BIM adoption

S/No.	Drivers to BIM adoption	Reference
1	Availability of trained professionals to handle the tools	[23,51,52,53]
2	BIM Software affordability	[54,51,55]
3	Enabling environment within the industry	[55,56]
4	Clients' interest in the use of BIM in their projects	[54,23,24,31,56,57,58]
5	Awareness of the technology among industry stakeholders	[23,55,59]
6	Cooperation and commitment of professional bodies to its implementation	[55,60]

7	Proof of cost savings by its adoption	[54,23,61,62]
8	Cultural change among industry stakeholders	[23,53]
9	Government support through legislation	[54,23,28,39,53,63]
10	Collaborative Procurement methods	[64]

3. Method

Review of literature (as secondary source) was the first step, serving as precedent and baseline to the study, primary data is also involved in this study and was collected within a period of five (5) months. An online questionnaire survey tool (google form) was used for the data collection. In an effort to determine the target population, interested parties were quite insignificant (in number) as the study subject awareness appear low [65]. A mixture of purposeful sampling and snowball method were adopted in sampling and data collection procedure. Purposeful sampling [66] was adopted to allow the researcher selects only the participants who possess the qualities necessary to provide meaningful input and reliable assessment of the study context and snowball [67] was utilised in generating substantial (in both quality and quantity) responses.

A quantitative research approach is adopted for this study. To achieve a wide coverage, considerable response rate, bias free response and free from privacy issues [68], quantitative research method therefore adopted. A structured questionnaire survey was used for the primary data collection. The questionnaire was designed mainly on two target enquiries, drivers and barriers to adoption of BIM in the Nigerian construction industry after determination of the respondent's demography. As it was set for a purpose, only those aware of BIM responses are accepted, thus the system accepts the only target audience.

Reliability test, descriptive statistics and Relative Importance Index (RII) were subsequently deployed for analysis of data. The reliability test was carried out to ascertain an internal consistency of scale of items used in the questionnaire as well as the reliability of questionnaire for further analysis. Descriptive statistics and RII are used the data analysis as to determine the most influential items and the interdependencies.

As for the respondents' profile, categorical data is generated while the main (enquiry) questions involved the use of five-point Likert rating scale with 5 as the highest rank and 1 the lowest.

Based on the five-point Likert rating scale, a standard method of ranking was used which is the RII.

RII is defined by the relationship as [54]:

$$\text{Relative Importance Index (RII)} = \frac{\Sigma W}{A \times N} \quad (0 \leq \text{index} \leq 1)$$

where:
W= weighting given to each element by the respondents.
i.e. between 1 and 5, where 1 is the least significant impact and 5 is the most significant impact;
A= highest weight; and
N= total number of respondents.
While the remaining are evaluated by simple descriptive statistics (in percentages).

4. Results

The reliability test result, respondents' demographic information, descriptive statistics on the barriers and the drivers as well as relative important index are evaluated and presented below.

4.1. Reliability test

As mentioned above, the reliability test was carried out to ascertain an internal consistency of scale of items used in the questionnaire as well as the reliability of questionnaire for further analysis. Thus, Cronbach's Alpha is adopted for the reliability analysis and the results are compared with George & Malley's [69] acceptability of any coefficient of

Cronbach's alpha greater than 0.6, as such all the items are within acceptable limit with Cronbach's Alpha coefficient of 0.95 (see table 3 and 4 below). All values >0.7 are considered acceptable [70], thus >0.9 indicated high level of internal consistency of items measurements and mean they are closely related.

Table 3. Reliability Test

Item-Total Statistics				
	Scale Mean if Item Deleted	Scale Variance if Item Deleted	Corrected Item-Total Correlation	Cronbach 's Alpha if Item Deleted
Availability of trained professionals to handle the tools	75.75	396.94	.68	.95
BIM Software affordability	76.09	396.80	.65	.95
Enabling environment within the industry	76.18	399.70	.69	.95
Clients interest in the use of BIM in their projects	76.15	391.14	.68	.95
Awareness of the technology among industry stakeholders	76.09	404.95	.59	.95
Cooperation and commitment of professional bodies to its implementation	76.16	397.78	.68	.95
Proof of cost savings by its adoption	75.94	406.62	.55	.95
Cultural change among industry stakeholders	76.54	402.52	.65	.95
Government support through legislation	76.51	389.18	.75	.95
Collaborative Procurement methods	76.46	394.25	.72	.95
Lack of expertise within the organisations	75.79	406.29	.52	.95
Lack of expertise within the project team	75.97	402.78	.58	.95
Lack of standardisation and protocols	76.04	397.71	.69	.95
Lack of collaboration among stakeholders	76.26	398.23	.70	.95
High Investment Cost	76.35	393.81	.71	.95
Legal issues around ownership, IP & PI insurance	76.69	397.38	.68	.95
Lack of client demand	76.21	398.20	.59	.95
Lack of infrastructure	76.40	394.21	.67	.95
Lack of government policy	76.24	391.41	.71	.95
Industry's Cultural resistance	76.31	401.95	.64	.95
Lack of additional project finance to support BIM	76.24	394.84	.72	.95
Resistance at operational level	76.62	405.82	.57	.95
Reluctance of team members to share information	76.26	398.74	.75	.95
Return on Investment (ROI) issue	76.60	401.86	.64	.95

Table 4. Reliability Alpha Value

Reliability Statistics	
Cronbach's Alpha	N of Items
.95	24

4.2. Demographic profile of respondents

The table 5 below presents the details of the respondents involved in the survey. The details include their location of practice in Nigeria, year of experience in the industry, size of their organisations, profession, specialisation and their highest qualifications.

Table 5. Analysis of socio-economic variables. *(Source: field survey, 2018.)*

Variable	Characteristics	Freq.	Percentage (%)	Total
Location of practice	North-Central	26	38.2	
	North-East	11	16.2	
	North-West	16	23.5	
	South-East	2	2.9	
	South-South	4	5.9	
	South-West	9	13.2	68
Years practice	< 5 years	14	20.6	
	5 - 10 years	27	39.7	
	11 - 15 years	15	22.1	
	> 15 years	12	17.6	68
Number of employees	< 10 personnel (Micro)	29	42.6	
	10 - 50 personnel (Small)	29	42.6	
	50 - 200 personnel (Medium)	7	10.3	
	> 200 personnel (Large)	3	4.4	68
Profession	Architecture	16	23.5	

	Building Engineering	1	1.5	
	Civil/Structural Engineering	30	44.1	
	Electrical Engineering	8	11.8	
	Mechanical Engineering	4	5.9	
	Construction Management	1	1.5	
	Quantity Surveying	7	10.3	
	Other:	1	1.5	68
Specialization	Contractor/Construction	19	27.9	
	Designer or Consultant	41	60.3	
	Client	4	5.9	
	Development Authority	4	5.9	68
Highest qualification	OND or HND	2	2.9	
	B.Sc./B.Tech./B Eng.	34	50.0	
	MSc/M.Eng.	25	36.8	
	PhD	7	10.3	68

There is considerably higher respondents from four out the six zones, this happened due to higher number of researchers' own network and considerable number of firms and construction works within North-Central and South-West specifically. The predominant respondents are having 5 to 15 years of experience in the industry and mostly (about 80%) came from micro (<10 personnel) and small (10 – 50 personnel) firms or organisations. In the case of their professions, specialties and educational qualifications, over 60% of them came from Architectural and Civil/Structural engineering backgrounds and working as designers/consultants and contractors (over 80%). And, more than 80% are first degree (B.Sc./B.Tech./B.Eng) and second degree (MSc/M.Eng.) holders.

5. Results

5.1. BIM awareness and usage

This aspect involves evaluation of proportion of those using BIM from those aware but not using the concept. Note that all the respondents are only those aware of BIM; whether the use it or not. Thus, the percentages reflect the only within targeted group (who are aware of BIM). A significant shift can be notice from the 2017 survey and this indicated substantial increase in the awareness and usage within the market (see fig. 1 below). The proportion of usage to awareness increased from 28%:72% to 54%:46% (fig. 2) based on those aware of BIM.

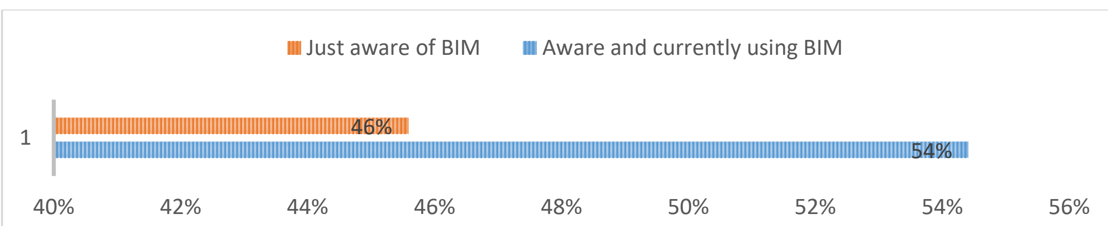

Fig. 1. BIM awareness and usage *(Source: field survey, 2018.)*

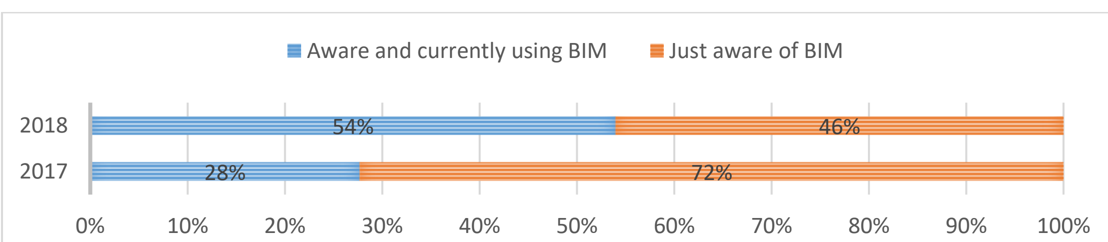

Fig. 2. BIM awareness and usage for 2017 and 2018

5.2. Barriers to BIM adoption in Nigeria

Subjecting the fourteen generated barriers to BIM adoption in Nigeria into RII (see table 6 below) using the scale of 1-5 (Likert scale), it was realised that, the 1st ninth ranked barriers are the most significant (RII ≥ 0.70) or mean ≥3.5 in a five-point Likert scale [71].

Table 6. RII and ranking of barriers against BIM adoption in Nigeria

Number of Rank *R* & Weighted value *W* impact	**Weight 5**	**Weight 4**	**Weight 3**	**Weight 2**	**Weight 1**	**Total**	**∑ *W***	**RII**	**Rank**
Lack of expertise within the organisations	110	92	39	10	5	68	256	0.75	1
Lack of expertise within the project team	90	92	42	14	6	68	244	0.72	2
Lack of standardisation and protocols	85	76	63	8	7	68	239	0.70	3
Lack of client demand	95	60	42	22	9	68	228	0.67	4
Lack of government policy	85	80	27	24	10	68	226	0.66	5
Lack of additional project finance to support BIM	75	64	63	16	8	68	226	0.66	5
Lack of collaboration among stakeholders	55	88	51	24	6	68	224	0.66	5
Reluctance of team members to share information	40	100	57	22	5	68	224	0.66	5
Industry's Cultural resistance	50	80	60	26	5	68	221	0.65	9
High Investment Cost	80	44	60	26	8	68	218	0.64	10
Lack of infrastructure	60	84	42	16	13	68	215	0.63	11
Return on Investment (ROI) issue	40	48	75	30	8	68	201	0.59	12
Resistance at operational level	30	56	81	24	9	68	200	0.59	12
Legal issues around ownership, IP & PI insurance	50	36	63	36	10	68	195	0.57	14

The result in general indicated lack of expertise within the organisations, lack of expertise within the project team, lack of standardisation and protocols, and lack of client demand as the most influential barriers (1st to 4th) respectively; and ranked the following as 5th: lack of government policy, lack of additional project finance to support BIM, lack of collaboration among stakeholders and reluctance of team members to share information.

5.3. Drivers to BIM adoption in Nigeria

Subjecting the ten generated drivers to BIM adoption in Nigeria into RII (see table 7 below) using the scale of 1-5 (Likert scale), it was realised that, the 1st seventh ranked drivers are the most significant (RII ≥ 0.70) or mean ≥3.5 in a five-point Likert scale [71]. The result indicates availability of trained professionals to handle the tools, proof of cost savings by its adoption, BIM Software affordability and awareness of the technology among industry stakeholders as the most influential drivers (1st, 2nd, 3rd and 3rd) respectively; and ranked the following as 5th: clients interest in the use of BIM in their projects, cooperation and commitment of professional bodies to its implementation, and enabling environment within the industry.

Table 7. RII and ranking of drivers against BIM adoption in Nigeria

Number of Rank R & Weighted value W impact	**Weight 5**	**Weight 4**	**Weight 3**	**Weight 2**	**Weight 1**	**Total**	**∑ W**	**RII**	**Rank**
Availability of trained professionals to handle the tools	130	84	24	16	5	68	259	0.76	1
Proof of cost savings by its adoption	85	88	57	12	4	68	246	0.72	2
BIM Software affordability	90	84	36	18	8	68	236	0.69	3
Awareness of the technology among industry stakeholders	70	84	57	22	3	68	236	0.69	3
Clients interest in the use of BIM in their projects	115	48	45	12	12	68	232	0.68	5
Cooperation and commitment of professional bodies to its implementation	80	72	48	26	5	68	231	0.68	5
Enabling environment within the industry	60	92	48	26	4	68	230	0.68	5
Collaborative Procurement methods	45	84	54	16	12	68	211	0.62	8
Government support through legislation	65	64	42	22	14	68	207	0.61	9
Cultural change among industry stakeholders	20	92	54	32	7	68	205	0.60	10

6. Conclusions and Recommendations

The urgent need for BIM adoption in construction industry is providing huge opportunities in research and development. However, researches in barriers and drivers to its adoption didn't yield fetched universal adoption thus, that leaves a question of inadequacy or misrepresentations. There are several findings on barriers and drivers to adopt BIM from literatures, many of which having different influence over the other. Nigeria is among developing countries where BIM is becoming vibrant however, BIM adoption in Nigeria still remains in its infancy. This piece of research is aim at filling the gap of differentiating by order of importance, the common barriers vis-a-vis to drivers toward BIM adoption in Nigerian construction market. This study contributes to the knowledge body by providing an in-depth understanding of potential barriers and drivers, their strength of influence and interactive relationships among barriers affecting the Nigerian construction industry as single body. Fourteen barriers and ten drivers were identified from literature, five Likert scale was used for measuring the respondents' perceptions and RII was used to rank the perceptions. Findings of this study discovered that 1^{st} to 9^{th} ranked barriers are very important (highly influential) against the adoption and 1^{st} to 7^{th} drivers are significant (highly influential) to facilitate BIM adoption in Nigeria. It is then recommended that, further evaluation should be made to compare the perception of those adopted BIM and those that haven't so as to determine percentage disagreement between the two groups; then further recommendation shall be made.

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A Mathematical model for quantifying workers' learning range on repetitive construction projects

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Abstract

The role of planning and management in the construction industry has always been significant towards improving project schedules. However, the impact of planning strategies on different construction schedules poses a margin for development and enhancement, especially when it comes to managing linear schedules or schedules of projects undergoing repetitive types of work. Previous research efforts developed models to individually analyze the influence of congestion and the learning curve factors on linear schedules, but failed to capture the combined complexities and dynamics when integrating both. Therefore, this paper puts forward the groundwork of a scheduling optimization framework and presents work targeted at quantifying the learning development range of construction workers on repetitive projects. The ultimate goal is to minimize potential congestions by taking into account the inherent uncertainties of linear activities while considering the learning curve effect. More specifically, three dimensions of uncertainty are considered for each activity, namely at the level of the activity itself, at the level of the activity and its predecessors, and at the activity-network level. At the heart of the proposed mathematical model is a fuzzy-based system that generates a minimum percentage reduction in productivity boundaries for each activity with different uncertainty dimensions. The presented fuzzy system will, in future work, become the foundation of a time-cost optimization framework for linear scheduling methods.

Keywords: Constructio;, Linear Scheduling, Productivity ; Learning Curve; Fuzzy Logic

1. Background

The learning phenomenon states that the time and effort required to complete any task decreases as the number of repetitions increases and further work experience is gained (Lam, Lee, & Hu, 2001). This concept, known as the learning curve effect, has initially originated in the airplane manufacturing industry (Wright, 1936). Subsequently, applications of this concept has spread through other sectors of manufacturing until reaching different areas in the construction industry (Hamade, Jaber, & Sikström, 2009; Hinze & Olbina, 2009; Lam et al., 2001; Wong, On Cheung, & Hardcastle, 2007; Zhang, Zou, & Kan, 2014). Other research works also considered the impact of the learning effect on different site activities such as prestressed concrete and piles (Hinze & Olbina, 2009), rebars Jarkas, 2010), formwork (Jarkas & Horner, 2011), and caisson construction (Panas & Pantouvakis, 2013).

More specifically, some research efforts incorporated the learning curve effect within scheduling techniques applied for repetitive projects, or what is called the line-of-balance (LOB) technique (Suhail & Neale, 1994) . The aim was to enhance the resulting schedules that are based on the false assumption of constant production rates while ignoring the

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effect of learning (Arditi, Tokdemir, & Suh, 2002). Other works have targeted this improved scheduling approach and included the effect of learning on LOB scheduling (Arditi, Tokdemir, & Suh, 2001), the obstacles and potentials when considering the learning effect in LOB scheduling (Zahran, Nour, & Hosny, 2016), and the modeling of the LOB scheduling with a learning development effect (Ammar & Abdel-Maged, 2018). Besides, many research works mentioned that maintaining work continuity in repetitive projects is recommended to minimize disruption and maximize the benefits of the learning curve (Ammar, 2012; Ammar & Elbeltagi, 2001; Elbeltagi, Elkassas, Rasheed, & Al-Tawil, 2007; Moselhi & El-Rayes, 1993; Thabet & Beliveau, 1994). Another recent effort worked on enhancing the precedence diagramming method by introducing two new precedence relationships (point-to-point and continuous relations) and while assigning either linear, non-linear, or learning curve production-time functions to activities (Hajdu, 2015; Hajdu, 2016). However, the author assumed a fixed production-time function for each activity without accounting for uncertainties that control their production variation range typically encountered in construction.

As such, despite the importance and the relevance of the learning curve effect in scheduling, in particular linear scheduling or LOB, the aforementioned literature addressing this matter is either ignoring the effect of learning, or assuming fixed or maximum learning in the productivity rates (Tokdemir, Arditi, & Balcik, 2006). Therefore, in order to enhance linear scheduling methods, there is a need to include a range of learning rates for each activity that best describes the maximum and minimum productivity boundaries. In other words, it is crucial to study the dimensions of uncertainty lying within each activity which, in turn, can directly impact the overall schedule. Therefore, this study defines three dimensions describing: (1) the flexibility of the activity itself, (2) the influence of the activity location on the project network, and (3) the overlapping impact of the activity on its corresponding predecessors due to the learning curve effect. As such, instead of only considering maximum learning rates, a synthesized degree of uncertainty, as explained above, can yield a minimum percentage reduction in the productivity boundaries defined by a decreased range of allowable learning rates. This process is made possible, in this study, through a fuzzy inference system (Garibaldi & John, 2003; Sivanandam, Sumathi, & Deepa, 2007) that appears as an attractive alternative for studying the impact of activities' uncertainty on productivity variations, and thus the overall schedule. Fuzzy logic is suitable for such a problem where there are incomplete or imprecise relationships between the variables under study (Chan, Chan, & Yeung, 2009). In this case, the proposed mathematical fuzzy system takes the activity's uncertainty dimensions as inputs and outputs a minimum percentage reduction in the original range of minimum and maximum productivity rates.

2. Proposed Model

2.1. Describing Activities' Allowable Learning Development Range

Prior to presenting the proposed mathematical fuzzy system and detailing its various elements, it is worth describing first the allowable learning development range for a certain construction activity. By looking at linear activities separately, each activity has a range of minimum and maximum productivity rates defined by the zero-learning rate (i.e. 100%) and the maximum learning rate, respectively. Figure 1 illustrates the original productivity boundaries for a certain construction activity, in particular the minimum productivity rate (line OA) and the maximum productivity rate (line OB). In this case, OA is assumed to have a constant optimized productivity rate with no learning. However, the curve corresponding to the maximum learning rate (OB) is assumed to be an average linear straight line following the Crawford's incremental unit time model (Jaber, 2016). For ease of calculation, the incremental time at the maximum learning rate of the Crawford's algebraic midpoint is considered the maximum productivity rate for all iterations and the cumulative average timeout at point B is computed using the learning curve function adopted from Malyuz and Pem (2013). As such, linear activities are governed by various project-based, activity-based, and interaction-based factors that can affect their productivity ranges. This thereby requires determining a new acceptable range (OA' - OB') within the original range of learning rates to account for all the inherent schedule uncertainties. The shaded area in Figure 1 indicates that the triangle OAB, bound by the original minimum and maximum learning rate curves, is minimized to a new allowable learning development region illustrated by the area OA'B'.

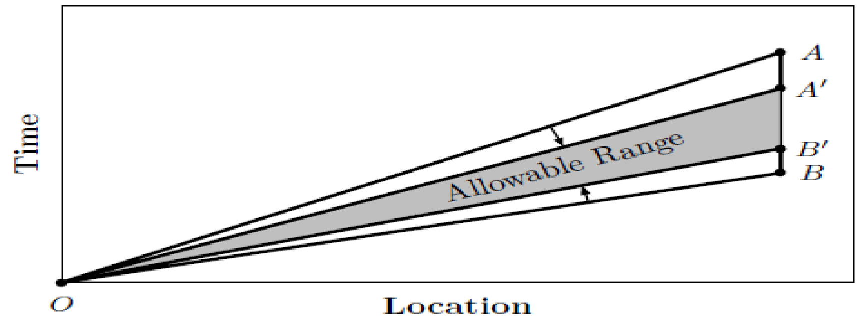

Figure 1: Space-time float of an activity

2.2. Presenting the Proposed Fuzzy Inference System Mechanism

Figure 2 illustrates the proposed mathematical fuzzy system.

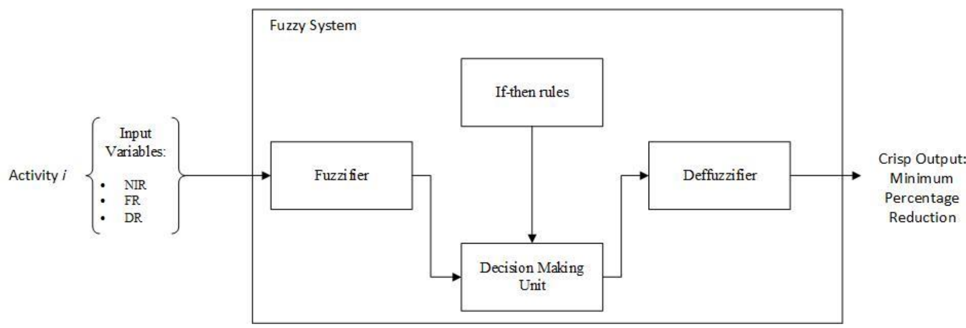

Figure 2: Fuzzy Inference System Mechanism

As shown in Figure 2, the impact level of an activity on the project network (i.e. NIR), the activity flexibility (i.e. FR), and the activity-activity overlap (i.e. DR) form the input variables (or attributes) of the fuzzy inference system, and directly affect the output. The output is actually the minimum percentage reduction in the area residing between the initial productivity boundary lines (Figure 1) and is quantified as follows:

$$\% = \frac{A_{OAB} - A_{OA'B'}}{A_{OAB}} = 1 - \frac{A_{OA'B'}}{A_{OAB}} \tag{1}$$

Another system component includes the fuzzifier which takes in the crisp inputs and converts them into a fuzzy number <0, 1> using its respective membership function. A membership function (MF) is a curve that mathematically defines the degree of an element's membership in a fuzzy set. The input variables are assigned degrees of membership in various classes or linguistic term sets (Wang, 2015). In this study, the suggested three input variables can have values of high, medium and low depending on the ratio. The subjective measures of these linguist terms are defined using either triangular or trapezoidal-shaped membership functions. After defining the fuzzifier component, the next step is to define the logical statements or the if-then rules. Fuzzy inference rules map input to output by feeding the decision-making unit of the fuzzy system with the ingredients to formulate decisions (Sivanandam et al., 2007). Typically, this intelligent component unit (Figure 2) assumes one of two formats in any fuzzy system, Takagi-Sugeno or Mamdani. Since the input in our system is intuitive and is expected to be provided by construction engineering experts, the Mamdani paradigm is applied (Sivanandam et al., 2007). Unlike Takagi-Sugeno, the output of a Mamdani fuzzy-based system is also fuzzy and a defuzzifier is thereby needed as depicted in Figure 2. Therefore, the output of the ruling process is defuzzified by converting it into a numerical format to generate numerical probabilities (i.e. percentages). For simplicity purposes, the defuzzification method used within this system is the Centroid of Area method (Wang, 2015) . It was selected since it returns estimates right at the center of the membership function curve; not too low or too high. The following subsection describes in detail the three input variables.

2.3. Defining the Fuzzy Input Variables

2.3.1. Network Influence Ratio (NIR)

The network influence ratio implies the relevance of a particular activity with other activities in the project network. It gives an indication about the degree of influence of a certain activity on the overall schedule. An activity's uncertainties and resulting delays and distortions are more likely to influence its succeeding activities and cause project delays, especially when the activity has a great number of successors. Thus, a larger percentage reduction in the productivity range is desirable for this activity. This ratio is measured as follows:

$$NIR_i = \frac{Ns_i}{Ns_i + Np_i} \tag{2}$$

Where, N_S is the total number of successors (direct and indirect) of Activity i, and Np is the total number of predecessors (direct and indirect) of activity i. NIR returns a value of 1 for the first activity as it has the highest number of successors and thereby impacts the schedule the most, and 0 for the last activity which has no successors.

2.3.2. Flexibility Ratio (FR)

This ratio is an input variable that is directly related to the space-time floats of linear activities and represents the flexibility of a particular activity. As previously mentioned, productivity boundaries are defined by the minimum and maximum learning rates and are used to generate a space-time float triangle for that activity (Figure 1). Furthermore, the most likely learning rate is crew-dependent, results in a productivity rate that lies somewhere between the activity boundaries, and its location implies how flexible an activity is. In other words, the closer the most likely productivity rate to the maximum productivity rate, the more flexible the activity. Considering that the project is scheduled with no learning for all linear activities, the most likely learning rates being far-off from the zero-learning rate can offer a greater amount of leeway for that activity. It has been found through previous studies that activities with less flexibility are less likely to be completed on time (Yang, Fu, Li, Huang, & Peng, 2008), and therefore less percentage reduction is required for these activities. Consequently, when the activity i has a low flexibility, it imposes a higher risk on the time completion of succeeding activities and accordingly requests a smaller percentage reduction of the space-time float. In contrast, a greater percentage reduction is witnessed for more flexible activities as they are less likely to delay succeeding activities. The value of the FR for Activity i can be determined as shown below:

$$FR_i = \frac{P_{most,i} - P_{min,i}}{P_{max,i} - P_{min,i}} \tag{3}$$

Where, P_{min} is the optimum productivity at zero-learning, P_{max} is the optimum productivity at maximum learning rate, and P_{most} is the optimum productivity at the most likely learning rate

2.3.3. Dependency Ratio (DR)

The importance of this ratio is manifested when the learning curve effect comes into play. It captures the degree of interference of the current activity with its corresponding predecessors, if it is performing work at a maximum productivity. In other words, it is important to identify the impact that an activity operating at a maximum learning rate has on its predecessor's learning development range. Due to repetition in linear projects, different activities operate at different locations simultaneously, and potential congestion may be created as a result of any deviation from planned productivity rates. Besides, the learning curve effect is a major factor causing productivity deviations in repetitive projects. Figure 3 presents the space-time floats for activities 1 and 2 each bound by their minimum and maximum productivity rate lines. More specifically, Activity 1 is bound by lines OA and OB while the productivity range of activity 2 lies within EC and ED. At zero learning, activity 1 (OA) and activity two 2 (EC) have a finish-to-finish relationship and an associated lag. At the maximum learning rate (MaxLR), the dotted productivity line (ED) of activity

2 intersects with the minimum productivity line (zero-learning) of its predecessor (i.e. OA). As shown in Figure 3, this interference creates potential congestion (shaded area) where the two activities have both spatial and temporal overlaps.

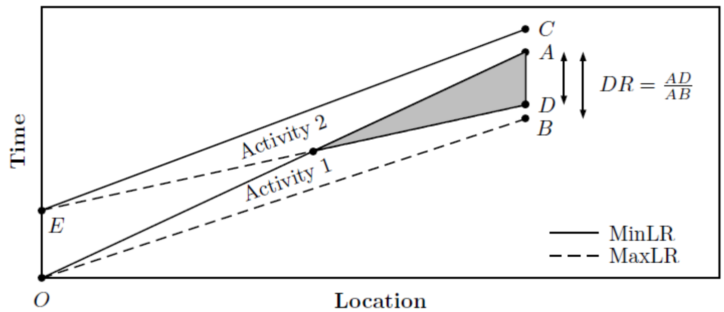

Figure 3: Space-time overlapping between activities

The equation below (Eq. 4) measures this overlapping impact as a dependency ratio between consecutive activities (refer to DR in Figure 3). The ratio is clearly controlled by both the progress and the learning rates.

$$\begin{aligned} DR &= \frac{AD}{AB} \\ &= \frac{Y_{P\min}(P) - Y_{P\max}(X)}{Y_{P\min}(P) - Y_{P\max}(P)} \\ &= \frac{\dfrac{1}{P_{\min(P)}} - \dfrac{1}{P_{\min(X)}} \times k_1^{\frac{\log LRx}{\log 2}}}{\dfrac{1}{P_{\min(P)}} - \dfrac{1}{P_{\min(P)}} \times k_2^{\frac{\log LRp}{\log 2}}} \\ &= \frac{P_{\min(X)} - P_{\min(P)} \times k_1^{\frac{\log LRx}{\log 2}}}{P_{\min(X)} - P_{\min(X)} \times k_2^{\frac{\log LRp}{\log 2}}} \end{aligned} \tag{4}$$

Where: k_1 and k_2 are the algebraic midpoints of the total number of iterations or repetitions in the project; X is the current activity and P is its corresponding predecessor; LRx and LRp are the maximum learning rates of the current activity and its predecessor respectively; Y_{pmin} (P) is the ordinate of point A; Y_{pmax} (X) is the ordinate of point D; and Y_{pmax} (P) is the ordinate of point B.

Therefore, an activity with a low dependency ratio is less subject to creating congestion with its predecessors and accordingly requires a smaller percentage reduction in its space-time float. Conversely, a greater percentage reduction is witnessed for activities with higher dependency ratios as they are more likely to interfere with their predecessors. Moreover, if the current activity has more than one predecessor, only the maximum dependency ratio is considered as the input and if the maximum productivity rate of the current activity doesn't interfere with the space-time float of its predecessors, the dependency ratio becomes zero.

3. Conclusion

It has been always stated that learning curves can significantly impact construction labor productivity. However, this impact can become negative in linear projects or horizontal repetitive projects where the deviations from planned productivity rates may lead to potential congestion. Some activities may undergo a maximum productivity improvement due to learning, while others might witness no improvement. In most cases, this phenomenon can lead to space-time overlapping between activities, thereby causing project delays. Moreover, the flexibility of the activity itself in addition to the activity influence on the project network can also impact the inherent schedule uncertainties. Therefore, given the three aforementioned uncertainty dimensions, the range of productivities, defined by minimum learning (zero-learning) and maximum learning rates, needs to be reduced to an allowable learning development range for each activity. As such, this paper presented a fuzzy-based system targeted at quantifying the learning development range for each activity of repetitive construction projects. The proposed fuzzy-based system takes in the uncertainty dimensions as inputs and generates the minimum percentage reduction in the activities' productivity range as output. These percentages will, in future work, be input into a time-cost optimization framework that aims at minimizing congestion in linear schedules while considering the learning curve effect.

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Applied decision-making framework for maintenance scheduling in bridge management

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Abstract

The deterioration of bridge structures in the United States is a national multibillion-dollar problem. Recent studies and reports show that almost 10% of these bridges need to be repaired or replaced. Therefore, facilitating decision-making for optimal bridge maintenance scheduling is essential for the management of networks of these aging structures where lack of preventative and proactive strategies cause significant consequences. In order to achieve such schedule, analytical methods are required to optimize conflicting factors over the life-cycle of the bridge while considering (i) structural performance and (ii) maintenance cost.
An advanced reliability-based decision-making framework for maintenance scheduling of deteriorating bridges is proposed. The outcome is a decision-making framework regarding repair and replacement of the structure over its life-cycle in terms of schedule and type of action to-be-performed on selected components considering system requirements, structure specification, as well as available budget. To implement the proposed framework, and in order to evaluate the performance of the developed methodology, a numerical experiment is developed. The results obtained by applying the methodology on an existing bridge are analyzed and the efficiency and advantages of the procedure are demonstrated.

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Keywords: bridge management; reliability-based maintenance scheduling; decision-making framework; multi-objective optimization

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1. Introduction

In recent years, in order to facilitate the efficient decision-making for scheduling maintenance for bridge systems, many performance models have been proposed, and various optimization methods have been introduced for obtaining the optimal maintenance plans using life-cycle performance and cost-efficiency in deteriorating structures. A class of these methods uses annual reliability index as a performance indicator where multi-objective optimization has been applied to reach the solutions. Most of these approaches deal with limited maintenance actions such as preventative measures [1, 2]. On the other hand, probabilistic models only deal with the uncertainties related to the indicators regarding the performance of the system, not the maintenance cost. Accordingly, in the previous methods, a comprehensive category for maintenance actions has not been considered, cost models have been assumed deterministic, and also optimization approaches have been bounded to a set of feasible solutions – not an optimal solution. In bridge management, optimal maintenance plans play a crucial role in the strategic decision-making. These

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plans have to address a number of conflicting factors and criteria. To achieve optimal or close to optimal plans, advanced analytical methods are necessary to optimize maintenance cost and increase the performance level of bridges.

In this paper, we focus on development of a maintenance scheduling method to enrich previous works and increase the efficiency of the maintenance decision-making process by overcoming mentioned limitations. The objective is to propose a decision-making framework for scheduling the maintenance of bridge superstructure as a multi-component system using multi-objective optimization to maximize structural performance – annual reliability index – and minimize life-cycle total maintenance cost to suggest a sequence of maintenance actions performed on selected components of the bridge. The approach is implemented on an existing deteriorating bridge superstructure. Main features of the approaches proposed in this paper include (1) considering a spectrum of maintenance actions including prevention, different levels for repair, and replacement, (2) performing optimization over probabilistic maintenance cost model, and (3) achieving ultimate optimal solution by solving optimization problem for Pareto frontier associated with optimal maintenance schedules of the structural system.

Infrastructure systems are subject to failure caused by several phenomena such as resistance reduction and increase of imposed loads, which lead to reduction of structural safety. When failure happens, repair or replace action is necessary. In order to keep the structure reliable, optimal maintenance strategy is required considering constraints, uncertainties, and economic factors during the life-cycle of the system. This needs an effective decision-making procedure and framework to reach optimality in planning. Methods and techniques for the determination of life-cycle maintenance strategies and plans have been extensively discussed in recent years and many approaches have been proposed. Advanced methods apply economic, environmental, structural and safety requirements to optimize time-dependent structural performance considering uncertainties [3].

Deterioration of existing structures due to increasing loads over time, environmental causes, and material properties have been studied over decades. If proper maintenance plan is not considered, this phenomenon leads to loss of reliability and serviceability of the structure as well as structural failure. In addition, obtaining economic plan and reducing unnecessary costs are required. Therefore, applying a cost-effective maintenance plan to avoid deterioration and damage is a significant problem in infrastructure systems, such as highway bridges.

Optimal maintenance scheduling of structures and infrastructures requires the development of methodologies for generating cost-effective optimal strategies for bridge maintenance scheduling including time and types of actions. Maintenance actions are categorized as (1) preventive, which is slowing down the structural deterioration, (2) repairing, and (3) replacing a failed or damaged component [1, 3, 4]. Among the techniques used in decision-making, multi-objective optimization can provide optimal solutions considering all complexities and limitations [3, 4, 5].

Uncertainties associated with load, environment, and material make the accurate prediction and planning complicated. Therefore, structural performance such as reliability should be predicted in terms of a probabilistic metric. In addition, uncertainties associated with time and cost make the exact prediction and planning impossible. Considering all of these uncertainties, the optimal maintenance scheduling for bridge structures should be reliability-based. In recent years, advancements in structural reliability theory and life-cycle stochastic optimization, have developed new tools and techniques for infrastructure systems analysis under above-mentioned uncertainties [1, 3, 4]. Therefore an advanced reliability-based maintenance optimization methodology for deteriorating bridges to find the optimum maintenance action sets including schedule and type of action is required. To generate such methodology for optimum maintenance scheduling procedure and to propose an applied decision-making framework associated with the life-cycle of the bridge, a multi-objective optimization considering total maintenance cost and system structural performance – reliability index – is necessary.

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As an advanced solution, maintenance costs and structural performance index are projected by exhaustive search and scheduling sets obtained by Pareto Frontier are applied in a multi-objective optimization method to report optimal maintenance schedules. This paper proposes an advanced methodology for determining optimal bridge maintenance scheduling based on probabilistic total maintenance cost and minimum annual system reliability index as structural performance metric through a decision-making framework. The approach is fully developed and programmed using the MATLAB® R2011b programming environment.

2. Methodology

Analyzing performance of structural systems of bridges is necessary for optimizing maintenance cost including repair and replacement. As a continuation of previous related works, which were focused on *replacement* strategies, this paper pursues an approach for optimizing *repair and replacement* in bridge maintenance. The aim of this paper is to propose a multi-objective method to optimize the cost for bridge repair and replacement using probabilistic performance indicator - system reliability index. This procedure is introduced in three phases. The first phase – preliminary – includes preliminaries for this methodology including data fitting, structural modeling, optimization parameter definitions, reliability calculation, and setting the policies. In the second phase – implementation – steps for repair and replace procedure are proposed. Multi-objective optimization is discussed in the third phase – optimization. We discuss these phases next.

2.1. Preliminary Phase

The input for the proposed procedure is the initial data including the bridge structural reliability model and reliability index for each independent bridge component available in a certain life-cycle. Reliability indices for each component over the bridge life-cycle are used for polynomial fitting in order to reach a complete set of reliability indices data for all years in the life-cycle.

By making appropriate series, parallel and combined system assumptions, we model the bridge structural system reliability. The reliability of a bridge structural system is evaluated by considering the system failure as series-parallel combination of the component failures. The primary assumption in the bridge superstructure reliability modeling is that the system failure is considered to occur when either deck fails or any two adjacent girders fail [6]. For instance, collapse of deck causes the system failure. This assumption is limited to the linear interaction between the components [6].

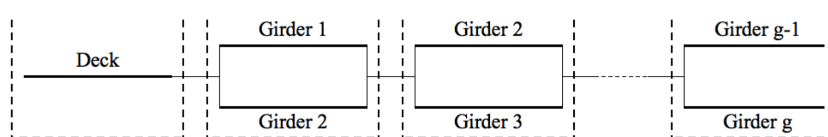

Fig. 1. System Reliability Model for the Bridge Superstructure

The system reliability model for the bridge superstructure is constructed by n sub-systems as illustrated in Figure 1. Each block, numbered 1 to n, represents a sub-system in this series structural reliability model. We show the deck with "D" and girders with "G". Sub-system 1 represents D, where sub-systems 2 to n are parallel model of two girders each. Structural reliability calculations for all sub-systems over the life-cycle of the superstructure are:

$$R_1 = R_D \quad \text{and} \quad R_i = 1 - \left(1 - R_{G,i-1}\right)\left(1 - R_{G,i}\right) \quad i = 2 \dots g \qquad (1)$$

Therefore, sub-system reliability calculations are obtained as following:

$$\beta_j = -\Phi^{-1}(1 - R_j) \qquad j = 1 \dots m \tag{2}$$

System Reliability (R_{sys}) is defined as the minimum of the sub-system reliabilities in a series structural reliability model [7]. Similarly, System Reliability Index (β_{sys}) is the minimum of the sub-system reliability indices. In the series structural reliability model, the system reliability index over life-cycle are defined as:

$$\beta_{sys} = \min\{\beta_i\}; \qquad i = 1 \dots m \tag{3}$$

where R_i and β_i are reliability and reliability index for i'th sub-system respectively and m is the number of sub-systems.

The defined number of condition states in the proposed approach is 1 to 5 that comprising of good, fair, poor, very poor, and severe respectively. According to [8], condition state for bridge components is estimated using a piecewise linear function of time as following by step – floor – function:

$$C = \lfloor 1 + \alpha t \rfloor \tag{4}$$

$$C^* = \begin{cases} C, & C \leq 5 \\ 5, & C > 5 \end{cases} \tag{5}$$

The constant piece of this function represents the maximum possible value for condition state after a certain deterioration condition, equal to 5. We set an action policy and define 5 different action types pertaining to each condition state including: a preventive action, three level of repair action, and a replace action. Examples of this setting are DOTs in the states of Minnesota, Colorado, and Florida. This general action policy is presented as following:

$$\begin{cases} CS = 1\,;\ Preventive\ action \\ 2 \leq CS \leq 4\,;\ Repair\ action \\ 5 \leq CS\,;\ Replace\ action \end{cases} \tag{6}$$

If the action type recognized as repair action, when condition state is between 2 and 4, the repair policy is applied as:

$$CS = x\,; Repair\ to\ CS = x - 1 \tag{7}$$

To determine type of repair/replace actions, we calculate boundaries over condition stated for each component.

We use exhaustive (brute-force) enumeration algorithm to generate all possible repair/replace (action) time sets in a defined life-cycle. Each subset is called a scenario. Therefore, for a bridge life-cycle of T_{LC} years, number of maintenance actions is considered as N_r. Minimum time between two consecutive maintenance actions is defined as T_Δ, and the efficient life-cycle for applying any maintenance action is T_{EF} years.

$$\begin{cases} t_{j+1} - t_j \geq T_\Delta\ years \\ t_{N_r} \leq T_{EF}\ years \end{cases} \qquad j = 1 \dots (N_r - 1) \tag{8}$$

Where t_{N_r} is the maintenance time. For example, we can set bridge life-cycle $T_{LC} = 75$, number of maintenance actions $N_r = 3$, minimum time between two consecutive maintenance actions $T_\Delta = 6$, and the efficient life-cycle for applying any maintenance action $T_{EF} = 60$. The outcome of the exhaustive enumeration model is a p-by-q matrix of scenarios times called TC, where $q = N_r$, and p is the number of all possible scenarios.

2.2. Implementation Phase

The objective of this process is to apply brute-force search over enumerated scenarios by determining to-be-repaired/replaced component at each selected time point in a scenario, applying appropriate repair/replace action, and updating components, sub-systems, and system reliability indices and condition states [9]. Using action policy and repair policy, we define target condition state corresponding to each policy. We use this information for updating the component reliability index and consequently re-calculating sub-systems and system reliability index for the remaining life of the superstructure. We need to recognize the component that requires repair or replace action. Considering enumeration search, we analyze each scenario one-by-one and report to-be-repaired/replaced component in each action time. To obtain this objective, we introduce three models based on different approaches for determining to-be-repaired/replaced component as following:

Model A: Component-based Approach

In this model, we define a sub-procedure, which is able to report an action binary indicator regarding each of n components at each action time where:

$$\begin{cases} \delta_i = 1; action\ required \\ \delta_i = 0; no\ action\ required \end{cases} \quad i = 1 \dots n \tag{9}$$

At each action time, the outcome vector of this sub-procedure contains $n-1$ component indicators equal to 0 and only one component indicator equal to 1; $\exists!\, i \le n\ (\delta_i = 1)$. Component with the indicator of 1 is considered as to-be-repaired/replaced component. The component corresponding to $\delta_i = 1$ has the minimum value of reliability index among all components at a time.

Model B: Sub-system-based Approach

In this model, in order to report an action binary indicator regarding each component at each action time, another sub-procedure is defined to assign an indicator to each of m sub-systems as:

$$\begin{cases} \theta_i = 1; action\ required \\ \theta_i = 0; no\ action\ required \end{cases} \quad i = 1 \dots m \tag{10}$$

and also to each of n components as:

$$\begin{cases} \delta_j = 1; action\ required \\ \delta_j = 0; no\ action\ required \end{cases} \quad j = 1 \dots n \tag{11}$$

At each action time, the outcome vector of this sub-procedure contains $m-1$ sub-system indicators equal to 0 and only one sub-system indicator equal to 1; $\exists!\, i \le m\ (\theta_i = 1)$, as well as $n-1$ component indicators equal to 0 and only one component indicator equal to 1, $\exists!\, j \le n\ (\delta_j = 1)$. Sub-system with the indicator of 1 is subject to action and component with the indicator of 1 is considered as to-be-repaired/replaced component. The approach to reach this outcome is to select the sub-system corresponding to $\theta_i = 1$ with the minimum value of sub-system reliability index among all other sub-systems at a time. As a result, to-be-repaired/replaced component is determined as the component with the minimum value of reliability index among all components in the selected sub-system.

Model C: Hybrid Approach

Two different models A and B use component-based and sub-system-based approaches respectively. The procedure in the approach of Model C starts with a comparison of outcomes from Model A and Model B at a time [9]. If those outcomes are similar indicating same component as the to-be-repaired/replaced, then the to-be-repaired/replaced component will be reported as the selected one in the Models A and B. If those outcomes report different components as the to-be-repaired/replaced, then Model C is activated. In this situation, a lower limit reliability index for a component is defined as β^l. Let's call the selected to-be-repaired/replaced components by Model A as Δ^A and by Model B as Δ^B. If the selected to-be-repaired/replaced component by Model C is Δ^C, we define the procedure for Model C as following:

$$If\ \Delta^A \neq \Delta^B\ then\ \Delta^C = \begin{cases} \Delta^A; \beta_{\Delta^A} \le \beta^l \\ \Delta^B; \beta_{\Delta^A} > \beta^l \end{cases} \tag{12}$$

Model C allows us to use the results of Model B considering the critical condition of the suggested to-be-repaired/replaced component by Model A. In other words, if the reliability index of the selected components by Model A is not less that defined lower limit, Model C prefers to report the selected component by Model B. The advantages of the hybrid model (Model C) are discussed in next section along with results and analysis. For each scenario obtained by exhaustive (brute-force) enumeration model, we use the outcome Model A, B, or C in order to (1) apply required repair/replace action, (2) update components, sub-systems, and system reliability indices, and (3) find Minimum System Reliability Index (β_{sys}^{m}) as the minimum value of the system reliability indices in the life-cycle of each scenario.

At each scenario, we calculate cumulative amount of future values for cost of actions for defined $\mathrm{N_r}$ actions to obtain total cost of action for the scenario. Using obtained action binary indicator δ for each component at each action time t, we can determine the cost of action C^a at each action time by using action binary indicators as:

$$C^a = \delta_1 C_1^* + \delta_2 C_2^* + \cdots + \delta_n C_n^* = \sum_{k=1}^{n} \delta_k C_k^* \quad (13)$$

where generally C^a represent the cost of an action at each time, and C_j^a indicate the cost of j-th action in a scenario. The total cost of action for i-th scenario CT_i is achieved as following:

$$CT_i = \sum_{j=1}^{N_r} \sum_{k=1}^{n} \frac{\delta_k C_k (1+i)^{t_j}}{(1+r)^{t_j}} \quad (14)$$

In the next phase, we convert multi-objective optimization for cost-reliability of superstructure.

2.3. Optimization Phase

We use “no-preference scalarized weighted metric method” for multi-objective optimization in order to find optimal solution among the Pareto Frontier obtained in the previous step. This multi-objective optimization method does not require any preference information to be explicitly articulated [10, 11]. The scalarized problem is formulated as

$$min \ \parallel f(x) - z \parallel_2 \qquad s.t. \ x \in X \quad (15)$$

where z represents ideal value preferred by the decision maker. This value for total maintenance cost (*tmc*) is the minimum value in the vector *CT* as:

$$z_{CT} = min(CT_i); \quad i = 1 \dots N_{par} \quad (16)$$

where *CT* (CostTotal) is a vector containing *CT*s for all possible scenarios.

The ideal for minimum annual system reliability index (*masr*) is the maximum value in the vector *BM* as:

$$z_{BM} = max(BM_i); \quad i = 1 \dots N_{par} \quad (17)$$

where *BM* (BetaMin) including the minimum value of system reliability index corresponding to each scenario, and N_{par} is the number of scenarios on the Pareto frontier. Therefore, our problem is modeled as following:

$$\varepsilon = arg\,min \ \mathcal{H}(BM, CT) := [(BM_i - z_{BM})^2 + (CT_i - z_{CT})^2]^{1/2} \quad (18)$$

The scenario corresponding to the argument ε is the optimal solution over Pareto frontier. By applying above procedure for multi-objective optimization of bridge repair and replace, we obtain optimal decision-making regarding the cost for bridge repair and replacement of the structure during the life-cycle. We present implementation of this process along with a numerical example next.

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3. Results and Analysis

To implement the proposed framework for reliability-based maintenance scheduling approach, and in order to evaluate the performance of introduced methodology, a numerical experiment is developed. This example shows the application of the methodology for any given bridge when the structural specifications and the life-cycle information are available.

The methodology is applied on bridge E-16-LY, Colorado (US Highway 36) built in 1985, in order to analyze the results. This bridge was introduced in [5]. This bridge superstructure contains three types of components; deck, interior girder, and exterior girder. This bridge has 3 spans. We implement the proposed procedure on the middle span of the superstructure of this bridge. The proposed procedure can be used with various bridges with different structures. In order to utilize this procedure for an existing superstructure, we need structural model configuration information and reliability indices of the bridge components (deck and girders) over the life-cycle as well as cost information of different type of maintenance actions for each component (replace and various levels of repair). We present results of applying the methodology for three models A, B, and C.

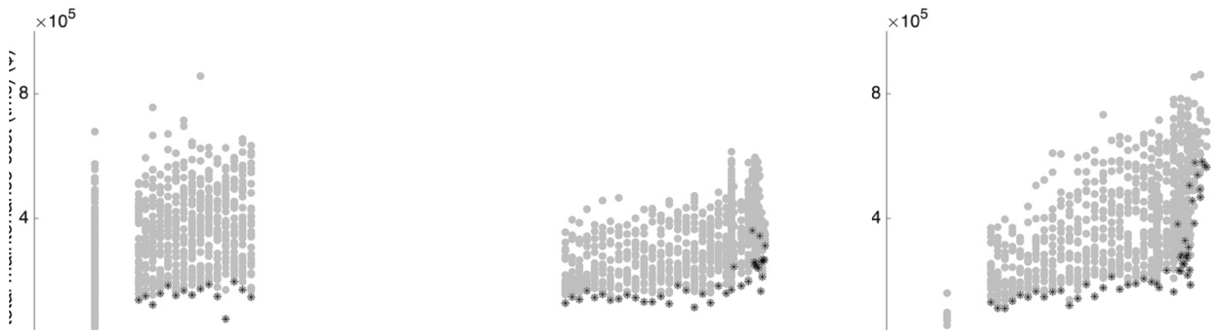

Fig. 2. Pareto Frontier (Black Asterisk) Bridge E-16-LY, Models A (left), B (middle), and C (right), $N_r = 2$

Figure 2 represents the obtained Pareto Frontiers of Models A, B, and C with two maintenance actions (repair/replace) for bridge E-16-LY, respectively. Comparison of the results of Model C to Models A and B shows that Model C (Hybrid Model) increases the efficiency of the proposed methodology which is (i) decreasing the total maintenance cost, or (ii) reaching greater minimum annual system reliability.

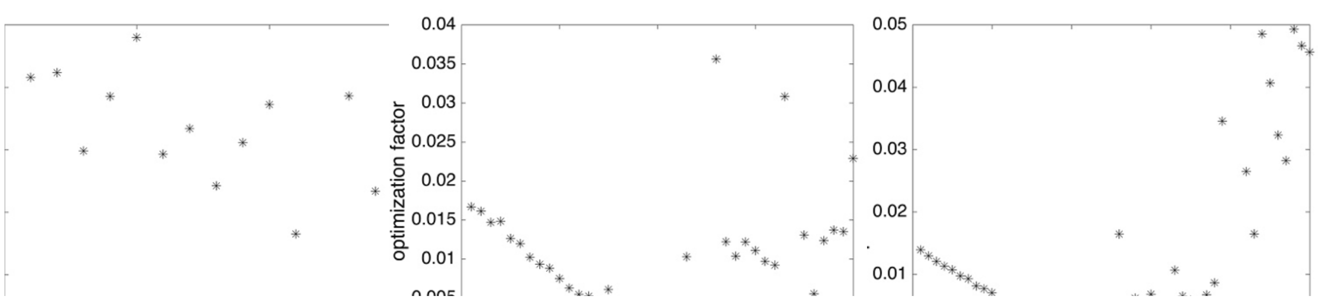

Fig. 3. Optimal Solution (Orange Asterisk) Bridge E-16-LY, Models A (Top), B (Middle), and C (Bottom), $N_r = 2$

Setting two required maintenance actions in the life-cycle ($N_r = 2$) and applying the procedure, the obtained Pareto frontier including selected candidate scenarios for each model is used as an input for the weighted single-objective optimization (sum of squared error) to report the best solution. By implementing "no-preference scalarized weighted metric method" for multi-objective optimization over each three obtained Pareto frontier sets for any subject bridge, we find the optimal solution among these selected scenarios. As a result of multi-objective optimization for minimum annual system reliability (performance indicator) and total maintenance cost, the optimal scenario is a scenario in the life-cycle of the subject bridge. This scenario suggests optimal maintenance actions. The results present types of actions contain to-be-repaired/replace component and the level of repair/replace, and also times of these desired actions. Figures 3 depict the optimal solution over the Pareto Frontier.

The optimal solution over Pareto Frontier (Orange Asterisk in Figure 3) in Model A is a scenario with the performance indicator value equal to 1.9264 and the maintenance cost equal to $77,713 (Scenario #12). These values for the optimal solution in Model B (Scenario #19) are 2.5113 and $129,316, where Model C (Hybrid Model) reaches the value 2.8920 for performance indicator and $164,607 for maintenance cost in its optimal solution (Scenario #25). Therefore the obtained optimal solution by Model C is more reliable and this model could reach higher values for $masr$ on the Pareto Frontier.

By applying multi-objective optimization over Pareto Frontier as a framework for partially evaluating feasible solutions, the optimal solution is obtained which satisfy one or more objectives, but not all. This optimal solution may change by considering boundaries and constraints by experts as "personal preferences of the decision maker". Under certain circumstances, cut-offs may be considered for performance indicator (reliability index) or maintenance cost, or both. Definitions of minimum annual system reliability ($masr$) by Departments of Transportation (DOTs) are different.

Experts may put a limit on "$masr$" and ignore an area of the Pareto Frontier by performance indicator cut-off, which eliminates some scenarios, and make the optimization more accurate, to the point. Also, if the maintenance budget is limited, proper cost cut-off may apply on the Pareto Frontier, eliminating some scenarios. Figure 4 depicts this concept for an example of minimum annual system reliability more than 2 and total maintenance cost (budget) less than $300,000 for the Model C Pareto Frontier of bridge E-16-LY.

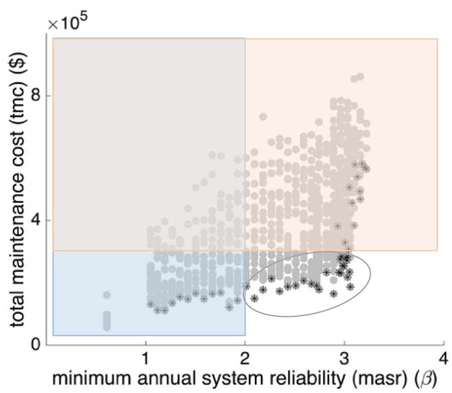

Fig. 4. Adjusted Pareto Frontier (Black Asterisk in Green Oval) Bridge E-16-LY, Model C, $N_r = 2$, $masr > 2$ (Blue Area Eliminated), $tmc < \$300,000$ (Red Area Eliminated)

4. Conclusion

Deterioration of bridge structures is a national issue in the United States. Facilitating decision-making for optimal bridge maintenance scheduling is crucial and plays a significant role in bridge management. Optimal maintenance schedule is required to keep the structure performing in a reliable manner considering constraints, uncertainties, and economic factors during the life-cycle of the system. To achieve this, an advanced and comprehensive analytical method is required to optimize maintenance cost and maintain or improve the structural performance of bridges.

Previous methods (i) lack a comprehensive category for the maintenance actions, (ii) assume deterministic cost models, (iii) focus on deck and girder replacement strategies only, and (iv) result in optimization approaches bounded to a set of feasible solutions – not an optimal solution. To advance previous works and to overcome mentioned limitations in maintenance decision-making process, a reliability-based multi-objective optimization methodology for bridges is proposed, where the condition states, the probabilistic annual maintenance cost and the system structural performance indicator – reliability index – are projected by exhaustive search and scheduling sets are obtained from Pareto Frontier.

The inputs to the procedure are (i) structural model configuration (reliability model) and structural specifications of the bridge components (reliability indices) including deck and girders over the life-cycle, (ii) probabilistic cost of different type of maintenance actions for each component including replace and various levels of repair, (iii) economic factors (annual discount and inflation rates), and (iv) desired number of maintenance actions over the life-cycle. The output of the procedure is a set of maintenance scenarios obtained by applying multi-objective optimization considering probabilistic cost model and a component-based and sub-system-based combinatorial analysis model to give multiple options to the decision-maker. These options contain performance metric and maintenance cost for each to-be-repaired/replace component and corresponding time of actions and type of action. The outcome of the developed system leads to optimal decision-making regarding repair and replacement of the structure during the life-cycle in terms of time and type of action with respect to system requirements, structure specifications, and available budget.

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Dynamic Planning of Construction Site

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Abstract

Dynamic planning of a construction site is an unexplored part of a project execution process, according to its absence in literature. The aims of this study are first to highlight this issue basically in linear construction projects and secondly to explore its value through practical applications. For this purpose, factors that influence the selection of the construction site location and then the costs resulting from this selection are examined. The location which maximizes the production rate is investigated. The location must simultaneously minimize the non-productive time/cost and adhere to project's technical specifications. According to the project's time schedule, the "ideal" site location is explored at time intervals taking into account the work progress. The optimization method that is presented aims to minimize the cost that arises from the site non-productive time/cost and site relocation cost as part of the total construction cost. The validity of the model is tested in two real case studies. The first study investigates a vertical axe to Egnatia Odos Motorway (5.5km) and the second regards a section of Egnatia Odos Motorway in North Greece (15km). The results show that for the second project the relocation is required, with a profit of 100.000 €, whereas for the first one, relocation has no profit for the contractor. The concluding remark is that during the planning phase of linear projects, a study of dynamic site location should be performed in order to investigate whether there is a profit for the constructor from the relocation of site or not. This profit could cover expenses of financing according to the project cash flows.

Keywords: Dynamic site planning, relocation profit, optimization, cash flows.

1. Introduction

Dynamic planning of a construction site is as an innovative idea not only targeting potential reduction of operating costs, but also pursuing increased safety levels during the construction phase of a project. However, the implementation of this process is a very challenging task due to the large number of different parameters involved in the selection of an appropriate initial location of the construction site. At the same time investigation of the potential benefits of its relocation must be performed according to the changing needs that arise from project progress. An optimization method is proposed with respect to the total operating costs by quantifying the combined effect of the cost factors involved in dynamic site planning.

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Thus far, studies on dynamic planning of construction site have been mostly focused on the effective placement of site layouts within the construction site and on their possible relocation after some time. What is ignored, is the effect of the construction site location on the total operating cost. This concept has been demonstrated through different methodologies with remarkable success, yet without considering the effect of a possible relocation of the construction site itself on the total cost of construction, safety and project duration. Cheng and O'Connor [1] developed an automatic site layout system called "Arcsite" to determine suitable areas for locating temporary site layouts in construction site. Some years later, Xu [2] demonstrated that dynamic layout planning is capable of minimizing the total operating cost and, at the same time, maximizing the safety measures on the construction site, proposing a fuzzy random multi-objective decision-making model to specify the parameters. Elbeltagi [3] presented a methodology for site layout planning, which combines the effect of safety, productivity, construction site area and the interrelationships between the necessary facilities on the total operating costs.

This paper investigates how relocation of the construction site in its entirety affects the total cost of a project. This unexplored idea despite the fact that seems relevant to the aforementioned researches, it is completely different; this research focus on the relocation of the whole construction site and not on the relocation of construction layouts into a specific construction site. In projects with several possible site locations, the focus is set on identifying the "ideal" one; being the most profitable acceptable location according to certain requirements. Therefore, criteria are formulated to determine acceptable locations for construction site and cost parameters of pertinence to the proposed methodology are discussed. Then, the "ideal" location, with respect to a specific sub-period of the construction process, is determined through the solution of an optimization process that minimizes the operating costs of the project. Eventually, the procedure is repeated for several non-overlapping sub-periods to obtain the "ideal scenario" for the entire construction period. The methodology is applied to two different road projects that have been already constructed to evaluate its potential for gaining significant cost savings.

2. Methodology

2.1. Location criteria

According to Building Regulation [4], there are several restrictions regarding the available locations for site construction. These restrictions include factors such as [5, 6, 7]:

- Availability of free spaces to host construction's site layouts [8].
- Existing electricity grid, water supply and sewage, to satisfy the demands of the site and the personnel.
- Ground morphology and quality. Some ground soils are not suitable for hosting a construction site [9].
- Environmental factors such as temperature, moisture, sun, rain.
- Ground slope. Slopes that are more than 17% [4], are considered unsuitable because of the high grade of resistance in the movement of the equipment that means higher transportation cost and waste of time.
- Legislative regulatory factors such as the use of land, biodiversity, archeology.
- The distance from public buildings such as hospitals, schools.

Taking into account these constraints, locations not fulfilling at least one of the requirements are not suitable for construction sites and therefore, they should be excluded from the following mathematical equation.

2.2. Cost parameters/factors

The following cost parameters/factors could lead to the "ideal" site location by minimizing the overall operating cost. For this research, the parameters that have been taken into account are listed below:

- Transport costs of workers and machinery. If the distance between the construction site and the workplace is long, then the transportation cost is higher. Especially for construction sites, where the transportation is intense, it is a crucial parameter.

- Duration of transportation for work. If the duration of transportation from the construction site to the workplace is long, then the production rate drops.
- Effect of acceptable slopes on the total cost. For steep slopes above 10% but below 17%, a modulation of the ground would be necessary.
- The influence of the morphology and the quality of the ground on the total cost. In case the ground is not suitable to host heavy facilities, soil reinforcement should be applied.
- Accessibility of construction site by trucks hauling material deliveries, fire trucks, ambulances.
- Accessibility from the construction site to the working site. In case there is no access, temporary site roads should be constructed.
- Preference of the decision maker. It is calculated as the total saving that the contractor would like to achieve in order to proceed the relocation of the construction site (it was taken equal to zero for this analysis).

2.3. The optimization equation

Five factors are embedded in the optimization equation for minimizing the total operating cost. The first refers to the transportation cost of the machinery from the construction site to the working site (and vice versa), while the second refers to the unproductive time due to workers transportations. The rest of the factors include costs related to ground formation, slope levelling and construction of the road network, as shown below:

$$TC(i,tp) = min\left\{ \begin{array}{l} fuel\ consumption \times fuel\ cost \times \sum_x \left(|x-i| \times\ transportation_{x,tp} \right) \\ \qquad + \ \dfrac{hourly\ wage}{machinery\ speed} \times \sum_x \left(|x-i| \times\ transportation_{x,tp} \right) + GRcost_i + Sl_i + RC_i \end{array} \right\} \quad (1)$$

where

i chainage of the controlled “ideal” location (m) and

x the chainages of the work sites in which the project is divided (m).

tp the time period, for which the quantities are taken into the calculation.

$Transportation_{x,tp}$ the total number of necessary transportations from the construction site (i) to the work site (x) for the machinery (trucks, excavator, concrete mixer) to execute a task, within the examined time period. This factor is the result of the quantities (m^3) for every task divided with the capacity (m^3) of the trucks.

fuel consumption the fuel consumption of each machine (lt/km).

fuel cost the cost of the necessary fuel that is used for the function of the machines, to execute the demanded tasks in the examined time period (€/lt).

hourly wage the average wage that the workers are paid per hour of work (€/h).

machinery speed the managed speed that each machine can achieve (km/h).

$GRcost_i$ the cost that is necessary in case that ground reinforcement is demanded (€).

Sl_i the cost that is necessary in case that slope leveling is demanded (€).

RC_i the cost for the construction of the road service network (€).

2.4. The “ideal scenario”

To identify the “ideal scenario” for the construction site of a project, the project manager should define the accuracy that would like to have in the analysis. This could be determined by setting a minimum time period in which the project manager would accept to proceed the relocation of the construction site and the density of the chainages in which the project is divided.

Specifically, in this research, the time period for a possible relocation is set 6 months or 1 semester and its multiples, and the total quantities of the materials (e.g. Concrete, steel, sewers) are divided in work sites with chainages increasing per 100 meters. In this way, it is possible to calculate the "ideal" location of the construction site not only for every semester (1, 2, 3.. N), but also for the combination of non-overlapping semesters [1+2, 1+2+3, 2+3, N+ (N+1)]. In addition, the total cost for each case is compared. Apparently, the "ideal scenario" is the one with the minimum total cost. The methodology is depicted step by step in Table 1.

For instance, supposing for scenario X, one relocation of the construction site at the end of Nth semester is examined. For the first time period which last from the beginning of the project until Nth semester, the construction site is established at the available location 'a', which is the "ideal" location for that period. The operating cost for that period and for that "ideal" location would be 'A' €. In addition, the relocation of the construction site is taking place. The relocation cost arises from the facilities that are used in the construction site, named 'R'. For the second time period, which last from the beginning of (N+1)th semester until the end of the project, the construction site is established at the available location 'b', which is the "ideal" location for that period. The operating cost for that period and for that "ideal" location would be 'B'. User Target (€) is the amount that the user would like to achieve in order to proceed the relocation of the construction site. In this way, for scenario X, it is possible to calculate the total operating cost 'X' that is the sum (A + R + B + user target).

The decision about the relocation of the construction site, is taken after comparing scenario X with the "ideal scenario". The "ideal scenario" is the one with the minimum total operating cost TC. At the first repetition of the methodology, the "ideal scenario" is the "ideal" location of the entire project, without relocation.

Table 1:Methodology for relocation of the construction site

Scenario X	**Site in chainage**	**Cost**
$1^{st}+2^{nd}$ +… + N	a	A €
(N+1) +…+ Last	b	B €
Relocation cost		R €
Total scenario cost		**(A+B+R+ user target*) = X €**
Saving or charge of the basic scenario		**(TC(i)-X) = Y €**

*in the analysis that equals to zero

The result of this comparison after the subtraction [TC ("ideal scenario") –X] = Y, indicates whether the relocation provides a profit to constructor or not.

If Y > 0, then the relocation is profitable, if Y < 0, then the relocation is not profitable.

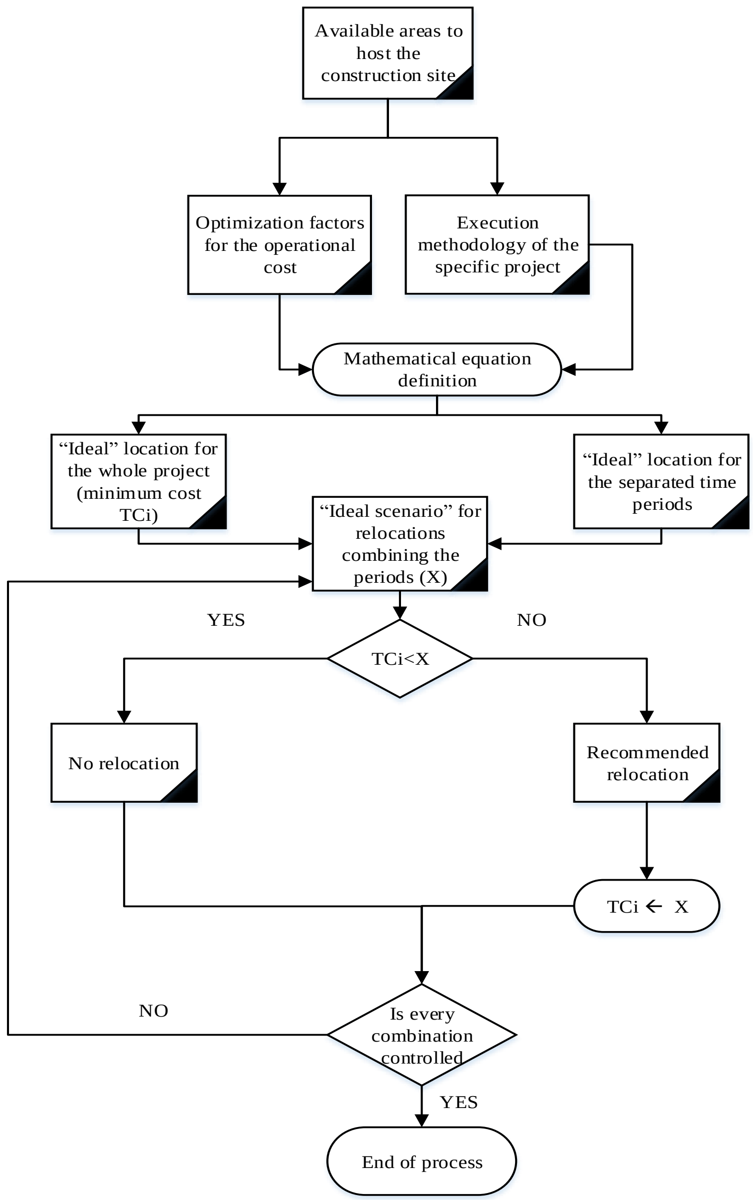

Figure 1: Methodology flowchart

The "ideal scenario" may include 2 or more relocations, so all the combinations of non-overlapping time periods should be controlled. The overall methodology is depicted in Figure 1. The process stops when no additional reduction on total operating cost of the project can be reached.

3. Applications and discussion

3.1. Case studies

The proposed methodology has been implemented into two road projects; the first project is a small vertical axe of Egnatia Odos Motorway in North Greece with a length of 5.5 km and a total cost of 25,000,000.00 €. The construction duration lasted three years from 2015 to 2018. The second project is a part of Egnatia Odos Motorway 15 km long and a total cost of 127,000,000.00 €, the construction phase of this project lasted also 3 years from 2004 to 2007. The available data for these projects was the topographic diagram, the horizontal alignment, the table of quantities of excavation and embankments, the table of technical works, the time schedule and the mechanical equipment needed for each work. The quantities of material were calculated for every 100 meters and the project duration was divided in semesters. All the data was saved in Microsoft Excel spreadsheets. For the optimization of equation (1) Evolver 7.5.2 of Palisade excel add-in tool was used. The ideal location for each scenario was then calculated.

According to the proposed methodology a cost saving of approximately 100,000.00 € was derived for the second case study. The relocation cost depends on the number and the size of site layouts. According to project managers for a typical linear project this cost might range from 30,000 € to 34,000 €.

Case study 1

According the project manager for the first project the machinery was transported from the construction site to the worksite, the products of excavation were not used for embankments, and the aggregates were stored in silos at the construction site. Thus, there were transportations from the construction site to work site. The mathematical equation resulted in that no relocation was needed and that the total operating cost for the "ideal" location was 104.507,36 €, whereas the cost of relocation was accordingly very high (Table 2).

Table 2 presents the total operating costs calculations, according to the examined location of the construction site. The first column depicts the number of the relocations that takes place in each scenario, whereas the second column shows the time period that the construction site would be established in the examined location. The fourth column indicates the operating cost of each scenario, and finally the last column calculates the profit or loss of each scenario compared to the "ideal scenario". This is essentially an application of the mathematical equation (1). That is, TC (1550, 1-6) = 142.044,10 € for the entire project. TC (i=3050, 1-3) = 39.127,72 € for the quantities of first to third semester. For the fourth to sixth semester, the ideal location is 2050. TC (i=2050, 4-6) = 83.604,51 €. So the total cost for this scenario is: TC (3050, 1-3) +TC (2050, 4-6) +Relocation Cost = 147.232,24 €, 42.724,87 € higher than the previous "ideal scenario".

Table 2: Analytically calculation of the total cost for the first project

Relocation	Time period	Ideal location	Operating cost	Relocation cost	Total cost	Profit/Loss
0	1st to 6th	1550	142.044,10 €	- €	142.044,10 €	- **37.536,73 €**
0	1st to 6th	Ideal =2650	104.507,36 €	- €	104.507,36 €	- €
0	1st to 6th	3550	122.580,05 €	- €	122.580,05 €	- **18.072,68 €**
1	1st to 3rd	Ideal =3050	39.127,72 €	24.500,00 €	147.232,24 €	- **42.724,87 €**
	4th to 6th	Ideal =2050	83.604,51 €			
1	1st to 4th	Ideal =3050	95.602,17 €	24.500,00 €	168.100,25 €	- **63.592,88 €**
	5th to 6th	Ideal =2050	47.998,08 €			
2	1st to 2nd	Ideal =4250	4.555,69 €	49.000,00 €	158.327,29 €	- **53.819,92 €**
	3rd to 4th	Ideal =2950	56.773,51 €			
	5th to 6th	Ideal =2050	47.998,08 €			

Case study 2

According the project manager for the second project machinery was stored on the work site, the products of the excavation were used for the embankments, the materials were delivered by trucks and the concrete was produced on site. The total duration of the project was 3 years (6 semesters) and the chainages were from 8+550 to 23+350. The available locations which could host the construction site were 9 (17 if only the slope parameter was taken into account, 41 if only the existing road network was taken into account). The total cost for the “ideal” location (i=14+850) of construction site without relocation is calculated 1.129.475,59 €. In this case, following the actual methodology of execution chosen by the constructor, the “ideal scenario” results in one relocation of the construction site (i1=14+650, i2=19+450) and the total savings are about 97.759,69 €. The relocation for this scenario should take place at the end of 4th semester. Table 3 presents the scenarios investigated.

Table 3: Analytically calculation of the total cost for the second project

Relocation	Time period	Ideal location	Operating cost	Relocation cost	Total cost	Profit/Loss
0	1st to 6th	11650	1.469.784,12 €	- €	1.469.784,12 €	**- 340.308,53 €**
0	1st to 6th	11850	1.436.149,95 €	- €	1.436.149,95 €	**- 306.674,36 €**
0	1st to 6th	14050	1.166.642,71 €	- €	1.166.642,71 €	**- 37.167,12 €**
(Scenario 1) 0	1st to 6th	Ideal =14850	1.129.475,59 €	- €	1.129.475,59 €	**- €**
0	1st to 6th	19450	1.363.944,17 €	- €	1.363.944,17 €	**- 234.468,58 €**
(Scenario 2) 1	1st to 4th	Ideal =14650	835.489,50 €	33.500,00 €	1.031.715,90 €	**97.759,69 €**
	5th to 6th	Ideal =19450	162.726,40 €			
(Scenario 3) 1	1st to 3rd	Ideal =14050	538.520,79 €	33.500,00 €	1.077.709,39 €	**51.766,20 €**
	4th to 6th	Ideal =19450	505.688,60 €			
	1st to 2nd	Ideal =14850	227.522,67 €			
2	3rd	Ideal =11850	289.677,88 €	67.000,00 €	1.089.889,16 €	**39.586,43 €**
	4th to 6th	Ideal =19450	505.688,60 €			
	1st	Ideal =14850	103.764,33 €			
2	2nd to 4th	Ideal =14250	726.713,93 €	67.000,00 €	1.060.204,67 €	**69.270,93 €**
	5th to 6th	Ideal =19450	162.726,40 €			
	1st to 2nd	Ideal =14850	227.522,67 €			
(Scenario 4) 2	3rd to 4th	Ideal =14050	599.960,19 €	67.000,00 €	1.057.209,26 €	**72.266,33 €**
	5th to 6th	Ideal =19450	162.726,40 €			

It is important for the successful completion of a project to safeguard financial viability throughout the construction period [10]. The proposed model of dynamic site relocation could help towards this objective. The cost savings of such a relocation process could cover financing costs. The following figures (1, 2 & 3) graphically present cash flows with cost savings in comparison among scenarios during the construction period by the adoption of a dynamic site relocation.

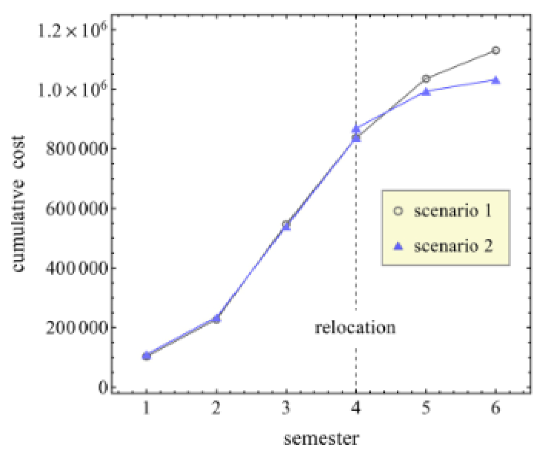

Figure 2: Operating cost cash flows scenario 1 vs scenario 2

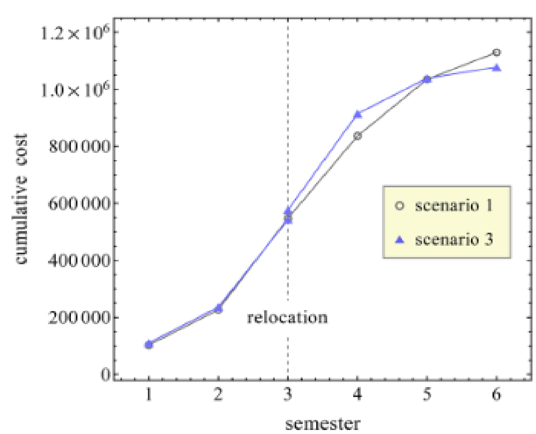

Figure 3: Operating cost cash flows scenario 1 vs scenario 3

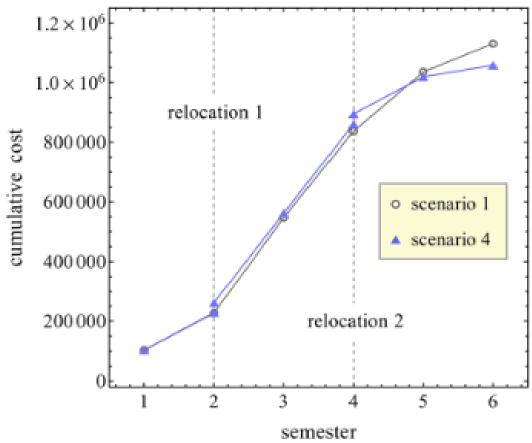

Figure 4: Operating cost cash flows scenario 1 vs scenario 4

Cost savings are developed after the relocation of the construction site, and especially at the 5th and 6th semester. This is explained from the fact that during the fifth and sixth semester the main tasks were executed at the last part of the road, which is from chainage 18+450 to 23+350.

3.2. Sensitivity Analysis

The methodology is sensitive to the way that the constructor chooses to execute the project. The sensitivity of identifying the ideal scenario for the location of the construction site could be clarified by the following hypothesis.

Case 1: It is examined the implementation of another execution methodology in the project, which include the division of the whole project in two parts, the first part from chainage 8550 to chainage 15550, and the second part from chainage 15650 to chainage 23350. In Table 4, it is presented two scenarios of this case. In scenario 1, after the completion of the first part, and the relocation of the construction site, the works on the second part start. In scenario 2, the first stage includes the execution of the earthworks and the relative technical works at the first part of the project, the second stage the execution of the earthworks and the relative technical works at the second part of the project and the third stage the execution of the asphalt pavement at the first and second part continuously. These scenarios are compared with the scenario 1 §3.1/case study 2 with total operating cost 1.129.475,59 €. Scenario 1 creates a profit of 532.881,89€.

Table 4: Total saving in case of change in methodology execution of the project

Scenario	Relocation	Task accomplished	Ideal location	Operating cost	Relocation cost	Total cost	Profit/Loss
1	1	8550-15550 15650-23350	Ideal =11850 Ideal =19450	258.293,48 € 304.800,23 €	33.500,00 €	596.593,71 €	**532.881,89 €**
2	2	8550-15550 (Earthworks and technical works) 15650-23350 (Earthworks and technical works) 8550-23550 (Asphalt paving)	Ideal =11850 Ideal =19450 Ideal =14850	157.274,60 € 177.154,92 € 463.106,64 €	67.000,00 €	864.536,16 €	**264.939,43 €**

Case 2: In case that the area between 15+000 to 23+350 was not available to host the site, then the "ideal scenario" would be without relocation of construction site, and specifically the construction site should be placed in chainage 14850 (scenario 1 §3.1/case study 2) and no profit earned.

Case 3: In case that there were no technical works, then the initial cost of no relocation scenario would be 897.115,19 € (scenario 1 §3.1/case study 2) and the total cost of the previous "ideal scenario" 826.891,27 € (scenario 2 §3.1/case study 2). For this hypothesis another scenario would be the ideal that for the relocation at the end of 3rd semester with total profit approximately 92.094,71 (scenario 3 §3.1/case study 2).

Case 4: In case that the machines were stored at the construction site, then for the scenario 1 with no relocation the total cost would be 2.243.701,07 € (scenario 1 §3.1/case study 2), and the "ideal scenario" would be for one relocation at the end of the 3rd semester with total cost 2.098.956,11 (scenario 3 §3.1/case study 2) and total profit of 144.844,95€.

4. Conclusions

A method of identifying the "ideal scenario" for the establishment of construction site was developed and then was applied to two different case studies to evaluate its effectiveness in terms of cost and safety. The results indicate that through the right and individual study of the execution methodology of each project, the constructor could achieve a significant reduction in the operating costs of the construction site, especially in large linear projects. In this way, it is possible for the constructor to cover any financial expenses during the execution period of a project. This research highlighted the areas that are more sensitive to cost increases from the appropriate construction methodology chosen. The relocation cost for a dynamic site organization is affected by the organization of the project team and the availability of resources. If the project is executed in different stages the profit is increasing remarkably.

Possible topics of future research would be in more depth examination of the impact of each factor in the total cost of construction site location. The proposed methodology should be tested in more case studies of linear projects in order to extract concrete results. Finally, this method should be implemented in an on-going project in order to quantify the impact (delay or acceleration of work site's tasks) on project's time schedule.

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Economic Based Limited Resource Scheduling Algorithm

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Abstract

Activity networks have been widely used in the planning, management, and control of building construction projects since their introduction in the 1950s. As the popularity of activity networking procedures has grown, so has the theory underlying the various procedures. Procedures are presently available that consider both technological and non-technological constraints and offer solutions solved optimally or heuristically. However, activity networks typical of building construction projects have not lent themselves to efficient optimal solutions because of their size, complexity, and diversity. Therefore, various heuristic scheduling procedures have been developed to solve this class of problem pragmatically if not optimally.

A disadvantage to the heuristic scheduling schemes available is that they follow a set of rigid heuristics and therefore may not be sensitive to a variety of differing network types or a variety of constraints. This study undertakes the development of a scheduling procedure that is heuristically based but that is sensitive to any variety of network types or constraints imposed by the scheduler. This is accomplished by combining all pertinent factors through a utility analysis and scheduling each activity based on the results of this analysis. The factors that are considered pertinent for the purpose of this study are the activity times based on technological constraints, network complexity, resource usage and availability, resource unit cost, and total activity cost. These factors are combined through the use of a cumulative utility model and prioritized to yield a scheduling sequence.

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Keywords: heuristic; limited; resources; scheduling; utility theory

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1. Introduction

Activity networks typical of building construction projects consist of a series of activities describing the technological sequence of events necessary for the completion of the particular construction project. Since construction projects are typically non-cyclical operations, the activities contained in the network are non-repetitive in nature [1]. The activities may also be described as unique, as they describe a number of different work activities in a number of different geographical locations, and they consume a variety of scarce resources in various amounts. The networks may also be quite large, consisting of hundreds or thousands of independent activities. As a result of the diversity of the activities and of the magnitude of the activity network, optimal solutions have not proven effective. Heuristic procedures have been used in place of optimality in order to achieve adequate results [2, 3].

The focus of this research is to evaluate the feasibility of scheduling a construction project based on any number of considerations that could impact the efficiency of the schedule. The underlying premise with a scheduling procedure is based on an ordinal utility ranking [4, 5, 6] that results in scheduling conflicts that will be reduced to a minimum if the activities with the highest utility values are scheduled first. It is important to keep in mind that the highest utility values are indicative of activities that require the most restrictive resources, are the costliest, and/or are the most restrictive in their placement within the network diagram. If many of the scheduling conflicts are eliminated from the outset, then the scheduling procedure should be more efficient than those used for similar types of problems.

In order to efficiently schedule the activities, each activity is assigned a utility value. The utility value can consider the aforementioned items or can be modified to consider any number of conditions deemed important by the scheduler [7, 8].

2. Scheduling Methodology

In order to schedule activities sequentially based on a concept other than time, it is necessary to use a scheduling procedure that treats time in a likewise subordinate fashion. That is, a scheduling procedure that is not based on the standard concept of beginning at day one and proceeding through the schedule a day at a time, scheduling activities as the resources are available until all activities are exhausted. The scheduling procedure must be flexible in that it allows the scheduling or time placement of activities in a random fashion yet does not violate any of the inherent technological or resource constraints of the activities.

In developing a computer program for such a procedure, efficiency is obtained by performing a minimum of checks where possible. Much of the scheduling procedure is devoted to performing checks for resource and/or technological constraints, but such checks are not required for the majority of the activities as the conflicts do not occur because of the basic premise of the scheduling procedure.

3. Scheduling Procedure

The scheduling procedure begins after the utility value for each activity has been determined. Beginning with the highest-ranking activity (the activity with the highest utility value), each activity is scheduled or assigned an appropriate time. As the scheduling does not proceed sequentially with time, it is first necessary to increase all activity times by a certain amount to facilitate backward scheduling as well as forward scheduling. For this study a value of 100 was added to all activity times, which proved to be sufficient for all activity networks tested.

Another preliminary consideration is the method of checking resource conflicts. As each activity is scheduled a resource profile is checked to see if the necessary resources are available during the appropriate time period. To facilitate this, a resource availability array is established with the available number of resources for each time period. Maximum limitations used in this study are 12 resources and 1000 days. The resource availability array established for a sample network was initialized with 35 units of Resource 1, 40 units of Resource 2, and a single unit of Resource 3. As activities are scheduled, the level of resources is reduced accordingly.

Activities are scheduled, as previously stated, by beginning with the highest-ranking activity and considering one activity at a time until all are scheduled. If resources are available in sufficient supply the project duration remains unchanged from the initial activity times as established without regard to resource requirements. If, however, the level of available resources is restrictive, the project duration will be extended. As the resource level is lowered, the project duration must be increased as more and more parallel activities are restricted to a serial placement. The scheduling of activities can be broken down into four different phases: (a) checking for resource availability, (b) checking network constraints, (c) resolving conflicts because of resource or network constraints, and (d) establishing activity times for each activity.

4. Resource Availability

The first consideration in the scheduling procedure is the availability of resources in sufficient supply to complete the activity as planned. The resources used by the activity are checked in order of the supply limitations imposed by the scheduler; that is, the resource that is most limited is first checked, the second most restricted resource checked next and so on. This is done as the most likely resource conflict will occur with the resource available in the most limited supply and if this is checked first any conflict is immediately determined and further resource checks are unnecessary.

Another consideration is given to the scheduled time placement of the activity. The activity is ideally placed between the early start time and the late finish time. If the activity is on the critical path as initially determined, there is no option as long as the required resources are available. The activity should be scheduled on consecutive days beginning with the early start time. If, however, the activity is not on the critical path there is some discretion as far as the time placement is concerned.

Most heuristic scheduling procedures will always attempt to begin an activity at its early start time. The reasoning, of course, is that if any conflicts occur it will be advantageous to know as soon as possible and alternate activities can be checked for possible scheduling. This is not a consideration if the scheduling procedure is not sequentially based on time.

The ideal placement of an activity is as close to its late finish time as practical. By doing so expenditures, for the activity are delayed and project funds are conserved. If activity time statistics are available as in a PERT analysis, a possible time placement for an activity would be one standard deviation from the late finish time as this would delay the start of the activity to a point where it would still be completed by the late finish time 95% of the time. As this study used a standard network analysis where activity statistics are not considered, a mid-point preferred placement time was selected. That is, an attempt is made to schedule the activity midway between its early start time and its late finish time. As activity scheduling can proceed either forward or backward from this point, the preferred placement time eliminates any bias in either direction.

If resources are not available in a sufficient supply midway between the early start time and the late finish time, the remaining time between the early start and late finish is checked for resource availability. The activity is scheduled within this time frame as close to the mid-point as possible. This, of course, is attempted as network constraints will not be in conflict if the resources required by the activity are available between the early start time and the late finish time. If resources are not available within this time frame, additional checks are required to locate a possible scheduling time for the activity.

The check for available resources outside the early start and late finish time frame is a two-part sequence as scheduling can proceed in either direction. First, beginning at the early start time and advancing in a forward direction a tentative scheduling time is determined. Next, beginning at the late finish time and advancing in a backward direction a tentative scheduling time is determined. The scheduling time that is selected is the one that is closest to the original early start or late finish time.

This process is repeated for each resource required by an activity. As each resource is considered, it is checked against compatible times established for the previous resources. At the completion of this phase of the scheduling procedure each activity is assigned a preferred time. This time is the closest time to the original early start-late finish mid-point in which all required resources are available.

5. Network Constraints

After all resources required by an activity are satisfied, the activity time established is checked against the activity times for all other work items in the network diagram. Stated another way, is the early start time established for this activity greater than or equal to the late finish time for all preceding activities and is the late finish time of the activity less than or equal to the early start time of all succeeding activities? If the activity times established are between the original early start and late finish times there will be no conflicts with other network constraints; if this is the case, the times for all activities within the network are simply updated to account for the specific time placement of the activity rather than the time range established initially.

If the time placement of the activity falls outside the rage of early start-late finish times, a conflict will occur with other activities in the network. If the conflict occurs with an activity that has a lower utility value (e.g., an activity that has not yet been considered for resource availability and scheduling), the activity times for the lower ranking activities are updated; establishing new start and finish times for the activity.

By considering the activities for scheduling in sequence based on their utility value, most of the conflicts that occur are resolved by updating the activities that have yet to be scheduled. If, however, a conflict occurs with an activity

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that has a higher utility value (e.g., an activity that has already been scheduled), this conflict must be resolved before further scheduling can take place.

6. Scheduling Conflicts

Scheduling conflicts that occur with activities previously scheduled are categorized into two groups. The first group consist of activities that are in conflict with a single previously scheduled activity and the second group consists of activities that demonstrate multiple conflicts.

In order to resolve the conflict that occurs between two activities, the scheduling sequence is reversed, between the two. This type of conflict would occur when Activity A was scheduled from day x to day y; and Activity C was scheduled from day x' to day y'. Activity B, with a lower utility value than A or C is to be scheduled as a successor to Activity A and a predecessor to Activity B and the duration of Activity B exceeds the difference between x' and y’. In order for activity A to be scheduled, one of the previously established constraints must be relaxed.

When this type of conflict occurs the resources that were previously assigned to Activity C are unassigned (i.e., returned to the resource pools) and Activity C is assigned a utility value just lower than the utility value of Activity B. That is, Activity A is scheduled, the activity times updated for B and C; Activity B is scheduled, the activity times updated for C; and finally, Activity C is scheduled without resource or network conflicts.

By reversing the scheduling sequence of only those activities in conflict, the remaining activities are unaffected and therefore the conflict is efficiently resolved. For example, if there are 100 activities in a network and a conflict occurs in the scheduling of the ninetieth activity, this activity and the conflicting activity are scheduled in reverse order without rescheduling other activities. If, however, there are multiple conflicts, this methodology would not likely result in efficiency as there would be a separate solution required for each conflict and these would have to be resolved simultaneously.

If multiple conflicts occur in the scheduling of activities, the activities in conflict are noted and scheduled before any of the other activities. If multiple conflicts occur repeatedly in the scheduling phase, the conflicting activities are successively added to the list of activities to receive primary consideration and the scheduling is restarted. As network complexity and resource restrictiveness increase, so do the incidences of multiple conflicts. The scheduling procedure as developed, resolved most multiple conflicts within a few passes of the scheduling sequence without adversely affecting the computational time required. The maximum number of multiple conflicts observed occurred in a highly resource constrained network. This network consisted of 97 activities and each required the use of eight resources. Forty-two multiple conflicts occurred before a solution was obtained and scheduling required more computational time of the same network with less restrictive resource requirements.

7. Activity Scheduling

Once all resource requirements are satisfied and all conflicts as a result of technological constraints resolved, the activity can be scheduled. By scheduling an activity, a specific time frame is assigned to the activity and the resources required for the activity are considered available only during this time. The initial early start, late start, early finish, and late finish times are therefore no longer valid. In place of these times is a start time and a finish time with the difference between the two equals to the duration of the activity.

As the times are assigned to the activity, the resources required are deducted from the available supply (e.g., the resource availability array) to prevent duplication of resource assignments. The activity does not change from this scheduled time unless a conflict is encountered as previously explained. The scheduling procedure is then repeated for the next activity in the utility ranking until all activities have been scheduled.

8. Results of a Scheduling Example

To illustrate how this process works a sample network of ten activities is used. The activities required the use of one or more of three resources limited in availability to 35, 40, and 1 unit per day respectively. Based on the resource requirements and limitations and the network constraints, the utility ranking is determined and used as a basis or sequence for scheduling.

The initial analysis of this network resulted in a project duration of 100 days but because of the resource restrictions imposed the duration was extended to 113 days. To schedule these activities only 10 iterations were required (i.e., no conflicts occurred with previously scheduled activities.

If this example is worked using standard resource allocation procedures based on early start times, as is typical of the most commonly used procedures, a similar schedule results. The major difference in the two schedules revolves around two activities. In the procedure developed for this study the activity with a high utility value is the second activity scheduled. The activity with a lower utility value is one of the last activities scheduled. This results in the scheduling of the first activity close to the originally determined activity times and the delay of lower ranked activity until adequate resources are available. This does not adversely affect the schedule as the first activity received a higher utility value be being on the critical path and the later activity has the maximum total float to work with.

Using a standard resource scheduling procedure, activities would be scheduled in a different order based, essentially, on time. This results in the delay of the project to a duration of 115 days which is slightly higher than the utility-based scheduling procedure.

9. Summary

In scheduling resource constrained networks, the final schedule is intimately dependent on the available level of resources. If all resources are available in unlimited supplies or more specifically in any degree required by a particular schedule, then the scheduling is effectively accomplished by an initial forward and backward pass. If the level of available resources is reduced to a point in which activities are forced to compete for the use of the resources, the scheduling of the activities becomes more critical if the original project duration is to be realized. That is, the activities must be assigned specific rather than general time placements in order to avoid delay causing resource conflicts. If the level of available resources is further reduced, the only option is to extend the project duration (assuming of course that the scheduling methodology is not to be changed). All resource constrained network scheduling procedures will accomplish this with varying degrees of accuracy.

There are basically two types of solutions to this type problem: optimal solutions and heuristic solutions. The optimal solutions have been shown to be either impossible or impractical for the majority of problems encountered with 'real world' construction scheduling. The heuristic solutions offer workable alternatives to the optimal solutions. The heuristic schemes deal with a comparative analysis of one scheme to another, that is, which is the best heuristic procedure - one based primarily on early start times, on late start times, on total float, on resource usage, etc. The answer of course is not general in nature and cannot generally be applied to all schedules. The important point is that each of these heuristic schemes is based on a non-varying set of heuristics. The procedures are not sympathetic to the specifics of the particular schedule.

By using a heuristic procedure that uses as a basis a criterion based on a combination of pertinent factors (i.e., utility value), an attempt is made to produce a scheduling procedure that is sympathetic to the peculiarities of the schedule. This is evident in that if a particular resource becomes more or less limited in supply, or if a particular resource becomes more or less expensive, or if a particular network diagram exhibits more or less complexity the sequence of scheduling these activities will change and, therefore, offer a different schedule. However, a difference in scheduling sequence may or may not offer a more favorable result. There is no heuristically determined scheduling sequence nor a basis for a scheduling sequence that results in the most efficient schedule for all network and resource considerations.

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Note: References are limited to background material, as the focus of the paper is original work of the author and to his knowledge has not been published before.

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Input for hybrid simulation modelling construction operations

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Abstract

Good pre-construction planning efforts are a vital part of the effective management and delivery of construction projects. In order to prepare more accurate schedules and cost calculations, realistic productivity rates to improve precision are needed. The use of simulation for modelling the elements of construction processes can assist with this aspiration. The application of hybrid simulation approaches is particularly appropriate as they can capture complicated behaviour, uncertainties, and dependencies. This paper discusses the use of one such approach combining discrete-event simulation (DES) and system dynamics (SD) to determine more accurate productivity rates. The DES component models the operations with the workflow of the tasks performed. Its input consists of the task elements with their durations and resource information. The factors that influence the productivity rates are taken into account with the help of the SD component. Input for this part of the model includes the factors as well as considerations of their interrelationships and effects. In this work, a case study of such input data for masonry works – for brick- and blockwork – is presented. It shows the input data and its integration in the DES-SD approach for modellers to determine more realistic productivity rates.

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Keywords: discrete-event simulation; labour; masonry; modelling; productivity; simulation; system dynamics.

1. Introduction

The construction sector contributes significantly to the world's economy; however, its productivity lags behind other sectors [1]. One of the contributing factors is the present shortage of skilled workers [2]–[4]. Because of this, more careful and accurate planning of construction operations is required. Therefore, it is important to have more realistic productivity rates and resource usage information, which can lead to more precise schedules and cost calculations.

Factors that influence labour productivity rates can be divided into two categories: the first contains those factors that only arise during the construction execution phase (for example, the weather), while the second category, which this research focuses upon, includes those that are known in advance, in the planning phase. For instance, in masonry construction, characteristics of walls and workers belong in the latter group. The specifications of the wall sections can be obtained from design drawings, while the characteristics of the workers are likely known by their supervisors and the contractors.

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This paper describes the input data needed for a DES-SD hybrid simulation model that could be used for obtaining better productivity rates. This includes the tasks of block and bricklaying processes for the DES component and the above-mentioned factors for the SD part. Before these are explained in more detail, the next section gives an overview of the studies on factors influencing productivity; it is then shown how simulation can be used in productivity research. Finally, the directions for further development of the model are set.

2. Factors influencing productivity

Studies on productivity comprise a substantial portion of construction research [5-6]. Much of these efforts have attempted to identify the factors that influence productivity, especially labour productivity, and group these into various categories. This is usually achieved in two ways. One is a synthesis of existing literature via systematic reviews as done, for instance, by Hasan et. al [2], who listed the factors according to countries and looked for common mentions. Another example is the work of Yi et al. [6], which describes the factors affecting labour productivity at industry, project and activity levels. The other option is to use survey research to uncover and prioritise the most important factors amongst those sourced via existing knowledge. See, for example, Naoum's [7] work, which considers 46 factors grouped into five categories (pre-construction, during construction, management, organisational, motivational and social). Several papers contain lengthy lists of factors, for instance, Dai et al. [8] identified 83 (at project level, grouped into the following categories: supervisor direction, communication, safety, tools and consumables, materials, engineering drawing management, labour, foreman, superintendent, project management, construction equipment), while Tsehayae and Robinson Fayek [9] instead collected 169 factors (grouped according to levels: activity, project, organisational, provincial, national, global). Some studies concentrate on a single country [10]–[13], while others compare and contrast their findings across several countries [14]–[16]. Numerous studies concentrate on the effects of individual factors on productivity such as the influence of project management [17], change orders [18-19], overtime [20], and the introduction of BIM [21].

In cases where surveys are used to determine the most important influencing factors, the results are likely to be affected by the sampling strategies employed and the groups of stakeholders responding. Hasan et al. [2] recommended to include various stakeholders. Kazaz et al. [22] and Dai et al. [8] presented the perspective of the craftsmen, while Alinaitwe et al. [10], Hanna et al. [20], Hickson and Ellis [13], and Proverbs et al. [14] compiled their lists from the contractors' point of view. Additionally, Ailabouni et al. [11] and Tsehayae and Robinson Fayek [9] asked both aforementioned groups: craftsmen and contractors. El-Gohary and Aziz [12] included clients, contractors, and consultants, as well.

There are research projects that focus on one specific work package, with masonry works being one of them. Anand and Ramamurthy [23] measured the productivity rates of the construction of different brick and block sample walls. Due to these observations taking place in a laboratory setting, such results can be used for establishing baseline rates, which are not affected by the factors typically involved in live construction site production. However, the various factors attributed to the workers can still influence the rates.

Thomas and Sakarcan [24] proposed the factor model to calculate productivity rates for masonry works. According to their model, factors (work type, physical elements, construction methods, design requirements, and squad size) were added to the base unit rate as coefficients. The values of the factors were obtained by collecting the daily outputs of several construction projects [24]. In a previous study [25], weather was also accounted for.

Thomas and Zavrski [26] found that the work content (i.e. complexity of design) was an essential influencing factor, as well; thus, a difficulty scale for masonry works was proposed. However, this only works at the project level. Thomas and Sudhakumar [27] suggested a multiple regression model to quantify the effects of influencing factors. Their list of factors included weather parameters, overtime, number of workers, and the aforementioned work content scale. Factors describing the complexity of the work are also part of Sanders and Thomas' [25], Thomas and Zavrski's [26] and Thomas and Sudhakumar's [27] models. However, in those models they characterised the entire project. This study considers the characteristics of the individual wall sections in order to obtain more precise productivity rates.

Olomolaiye [16] studied the effects of motivation and the workers' skills on productivity. He defined skill as a combination of experience, training, and natural ability. The conclusion of his study was that the effect of skills was greater on productivity than that of motivation [16]. Sweis et al. [15] also included skills in their list of productivity influencing factors. There skills contained training, work ethics, and motivation. This study also considers the effects of the characteristics of the bricklayers, i.e. their abilities and experience, on labour productivity rates.

Finding the most important factors affecting productivity may be difficult due to many factors acting simultaneously; therefore, defining individual effects may prove challenging. The combined effect of several factors is possibly not equal to the sum of the effect of each one acting alone, owing to their interrelations and dependencies [28]. The use of simulation can be helpful in determining the individual and combined effects of the factors.

3. Use of simulation for productivity studies

Simulation can be useful when experimenting on the real-world system would be too expensive, or risky. Therefore, simulation is suitable for analysing construction processes to answer questions about productivity. In the following, examples are shown for the application of basic simulation methods (discrete-event simulation, system dynamics, and agent-based modelling) and hybrid simulation approaches in productivity studies. Hybrid simulation approaches are the combinations of basic simulation methods with each other or with, for instance, fuzzy logic (FL).

Mawdesley and Al-Jibouri [29] attempted to identify the most important factors affecting productivity, their interrelationships and quantified effects through surveys filled in by construction experts. The developed SD model was used to evaluate different strategies and concluded that management should concentrate on planning and control. The concept of Nasirzadeh and Nojedehi's [30] model is similar, as well as the set of project-level influencing factors. Palikhe et al. [31] used SD to determine the most important factors affecting productivity in Nepal. Choi and Bae [32] also applied SD to integrate the effect of various continuous factors into their static estimation model. Olomolaiye [16] used SD to find the critical tasks of the process of bricklaying.

Both Al-Tabbaa and Rustom [33] and Han and Halpin [34] recommended the use of probabilistic over deterministic models and applied DES. The former researchers' model aimed to provide planners with activity and project durations with the help of DES using historic duration data and current site conditions. The latter researchers used DES to increase the amount of data input into a multiple regression model while taking a limited number of influencing factors into account.

Agent-based modelling (ABM) was applied by Watkins et al. [35]to analyse how the efficiency of the workers changes due to site congestion. Two different agents were defined: tasks and workers. The latter ones are characterised by their skill levels.

Alvanchi et al. [36] proposed the combination of DES and SD as the former is suitable for modelling the operation level, while the latter can contain context level variables; thus, allowing the creation of a more accurate model of construction operations. Alzraiee et al. [37] applied the same hybrid simulation approach to get productivity rates. The factors affecting these rates were considered with the SD component.

AbouRizk and Sawhney [38] developed a DES-FL hybrid system which provided the users with beta distribution functions of the activity durations to be applied in schedules. The input data included the selected factors, the likelihood of their occurrence, and their adverse effects. The last two were given in linguistic terms. The estimated minimum and maximum durations also had to be given. The result depended on how accurate information the user could provide.

Nojedehi and Nasirzadeh [39] presented an SD-FL hybrid model, which can be used for determining whether a certain managerial decision will, in fact, increase productivity. The SD part contained the factors influencing productivity, while their effects were quantified with the help of the FL component. Robinson Fayek and Tsehayae [40] recommended the application of hybrid FL approaches for the same reason. However, it was noted that the nature of FL limited the number of influencing factors; therefore, sub-factors were required to be introduced.

Khanzadi et al. [41] suggested an SD-ABM hybrid simulation approach to improve productivity. The SD component contained the influencing factors, while the ABM part had groups of workers as agents and was used to model site congestion.

Since the objective of this research is to create a model that will provide productivity rates while also considering factors affecting productivity in masonry works, a hybrid simulation approach has been selected. One component is DES because this will give the durations and resource usage data needed. The other is SD for its ability to show the interrelationships of the factors that influence labour productivity. The structure of the model is explained in a previously published paper [42]. The next section describes the input data necessary for each component.

4. Input for simulation

4.1. Input for the SD component

The SD component of the model comprises of the factors affecting labour productivity rates of masonry works with their interrelations marked and their effects on the productivity rates expressed. It is worth noting that a vast number of factors can be considered; however, this research project concentrates on the information available in the planning phase of a project. At this stage, data on the wall sections and bricklayers are accessible. These can be further divided into sub-groups as shown in Figure 1.

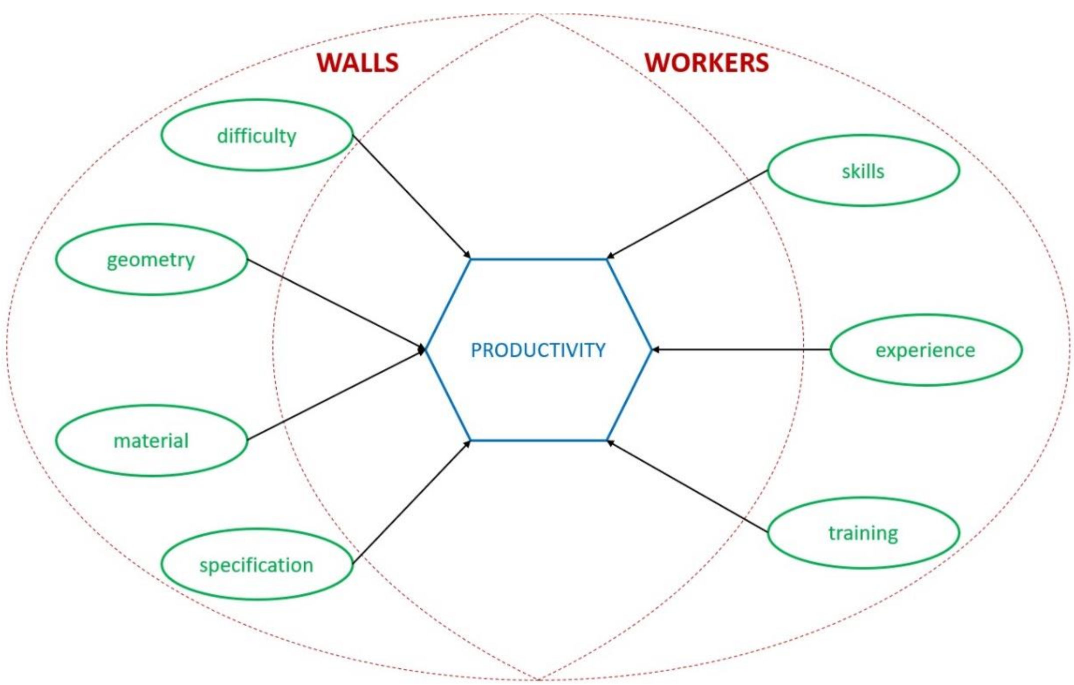

Figure 1. Factors affecting labour productivity rates of masonry works

The sub-groups contain the factors that make up the SD component of the model. For example, the difficulty sub-group includes the factors that determine how complicated it is to construct a given wall section. These are, for instance, the number of openings, cut bricks/blocks, and movement joints. The specification sub-group involves the pointing type and the type of bond required by the design. Figure 2 shows two possible bonding arrangements: the more common and simpler stretcher bond and the more complicated Flemish bond. The construction of simpler walls is generally faster.

Figure 2. Left: stretcher bond, right: Flemish bond (Orsolya Bokor ©)

The sub-groups associated with the workers are listed on the right side in Figure 1. For example, the skills sub-group includes factors such as the workers' abilities to work independently, without continuous supervision, and their own technical knowledge.

4.2. Input for the DES component

For the DES component of the model the main input are the tasks of the masonry construction process. The workflow of building a block wall is shown in Figure 3. The process starts with the preparation when labourers make ready stacks of blocks, place mortar boards on a number of these, and distribute mortar on them. The next activity is marking the location of the wall section to be built. This is either done by the foreman or by the bricklayers themselves. Laying the base course is crucial. After that the bricklayers build corners at each end of the section, and continuously check the laid blocks with tape measures and spirit levels. The blocks in-between can be laid to the line stretched between the corners. Once they reach scaffolding height, meaning that they can no longer work from the ground, the scaffolding needs to be assembled. Before that, pointing (i.e. tidying up of the joints) is performed and the surface is brushed. After the scaffolding is erected, the work continues in the same way as before until the wall section is finished. When the maximum height is reached, the last step is the final round of pointing.

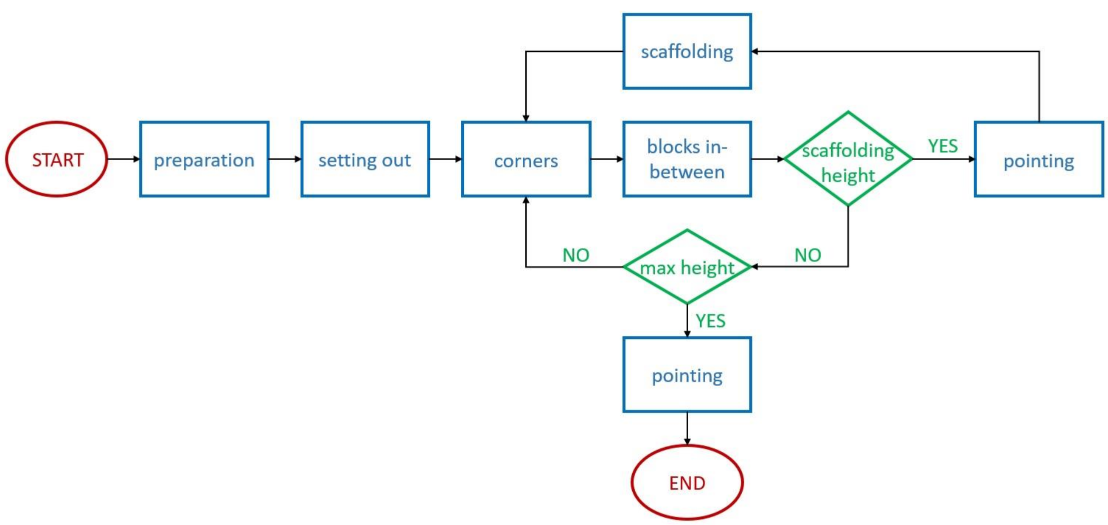

Figure 3. Workflow of blockwork

Another important type of input for the DES component is resource. There are various resources needed for performing the tasks, however, this research focuses on human resources. There are two such labour resources: bricklayers and labourers. Bricklayers start with the setting out, work until the scaffolding needs to be erected by the scaffolders, and then return, and stay until the end. Labourers are present throughout the whole process as they are responsible for unloading and distributing materials, which are mostly building blocks and mortar but different sorts of ties and movement joints are also needed. Generally, bricklayers work in squads of two or three depending on the length of the wall section with one labourer helping them.

The final group of input for the DES is the task duration. These are the interface variables providing the connection between the model's two components as their value is affected by the SD part.

5. Conclusion

The planning phase of a construction project is important. Accurate productivity rates and resource usage information are essential at this stage. Hybrid simulation approaches can be used for obtaining these. After selecting the most appropriate approach and determining the structure of the model, the input data need to be collected [42]. This is a crucial step as the output will only be as good as the input. To help with this phase of model development, this paper presents the necessary input data for a DES-SD hybrid model which is intended for providing planners with more realistic productivity rates of masonry works.

For the SD component, the list of factors that affect productivity rates needs to be compiled. In this case, it consists of the characteristics of the wall sections and the bricklayers. The interrelationships amongst the factors and their effects are also included in the input data for the SD part. For the DES component representing the workflow, the tasks with their durations and resource requirements comprise the input data. The task durations serve as the interaction points between the two components of the model. Their values are influenced by the SD component.

After the input data are available, the next step is to create the model and run the simulation [42]. Based on initial results, it needs to be refined, then verified and validated with data from real-life projects.

In the future, it needs to be explored whether other hybrid simulation approaches could also be used for the purpose of obtaining more accurate productivity rates. The results of this and the new models should be compared to determine the most suitable one. Moreover, further groups of influencing factors could be input into the model.

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Mining Daily Work Report Data for Detecting Patterns of Construction Sequences

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Abstract

Sequencing construction activities in highway projects is a complex planning process which requires not only considerable knowledge and practical experience of the planner/scheduler about various relevant aspects, such as the activities themselves, construction and procurement processes, and construction methods, but also input from other key members of the project regarding specific constraints and requirements. Moreover, sequencing is an iterative process; the sequence developed in the planning phase is likely to change in the construction phase. Therefore, learning from as-built schedules of past completed projects is needed to improve the planning and scheduling processes for future projects. In current practices, most state Departments of Transportation (DOTs) still mainly rely on schedulers' experience for schedule development. A data-driven systematic approach is still lacking, although the highway agencies have been spending a significant amount of money, time, and effort to collect various digital data during the construction process. This study aims to leverage historical digital daily work report data available in the DOTs' database to detect patterns of construction sequences in highway projects. Daily work report data collected from a state DOT were used to conduct a case study that developed a Sequential Pattern Mining algorithm to extract frequent sequential relationships among the activities for one major type of highway projects.

Keywords: Activity sequencing; Construction sequences; Daily work report data; Project scheduling; Sequential pattern mining.

1. Introduction

Schedule development is an essential component of construction planning that have a critical impact on successful project delivery [1, 2]. An optimized schedule enables the contractors and owners to complete a project on time with the minimum resources [3]. Schedules are a valuable tool to support project stakeholders in communicating and coordinating construction activities, track construction progresses after construction starts, and analyze and quantify the potential impact of delays on the overall project schedule. Developing a realistic schedule is challenging for inexperienced as well as experienced schedulers [4]. It is a complex process and requires knowledge of construction methods, materials, and labor productivity [5]. An as-planned schedule development typically consists of three steps: a) identification of activities through work breakdown structure development for the given project, b) determination of the duration of each activity, and c) determination of a logical and realistic sequence of activities [4]. Many academic

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studies have focused on the first two steps: a) identifying construction activities and b) determining activity durations using historical and reliable production rates to enhance the accuracy of schedule development [6, 7]. Regarding determining the sequence of activities, many studies pointed out the heavy reliance of owners and contractors on the experience and knowledge of experienced schedulers as the single most crucial source [5, 8].

In the highway industry sector, some Departments of Transportation (DOTs) such as Oklahoma DOT and Texas DOT have developed a set of scheduling templates that store a typical sequence of activities for a specific type of project to facilitate their scheduling activities. This approach helps capture and take advantage of experience schedulers' knowledge even after their retirement. However, such an approach has at least three significant limitations. First, it relies heavily on the experience of a scheduler to develop such templates. Second, various types of projects may have different construction sequences; multiple templates will need to be developed manually, one for each project type. Third, construction means and methods may evolve, and such static sequencing templates may become outdated.

In addition to these schedule templates, if there is a systematic approach to discovering the knowledge of precedence relationships of activities from historical projects and having the knowledge available for schedulers, it would greatly empower schedulers in gaining confidence in developing a new project's schedule and also help an inexperience scheduler to develop a schedule with substantial evidence. More than thirty DOTs have started to use digital Daily Work Reports (DWRs) which contain rich project progress and performance data at the construction activity level. This digital dataset can be directly used to discover various sequences of construction activities when appropriate data analytics is employed. This study applies a powerful Sequential Pattern Mining (SPM) algorithm to readily available historical DWR data to discover precedence relationships of activities.

2. Background

2.1. Prior studies

Prior studies suggest that schedules are mostly developed manually, especially in activity sequence development [6]. Existing studies on generating activity sequences have been focused on utilizing the expertise of experienced schedulers or logical assumptions about construction activity sequences. For example, Jeong et al. [8] developed fourteen different highway scheduling templates based on the Oklahoma DOT schedulers' experience. Bruce et al. [5] utilized a list of controlling activities and developed templates based on experts' inputs for 12 types of road and bridge construction projects. They also studied the resident engineers' project diaries and other project documentation to develop the templates.

In the vertical construction, some studies that were conducted to improve scheduling practices can be conceptually adopted to the horizontal construction. Cherneff et al. [1] developed a systematic approach to generating activity sequences by assigning various component constraints, i.e., physical constraints based on the construction components. An example of such component constraint is that a door can only exist in a wall. Therefore, a wall must be constructed before a door is installed. Echeverry et al. [2] used the similar approach with four types of logical assumptions: a) physical relationships between building components, b) interaction of construction trades, c) interference-free path for the movement of construction equipment and materials, and d) safety considerations. Similarly, Fischer and Aalami [4] generated component-constrained and activity-constrained relations. In a study by Kim et al. [6], identification of construction activities was improved by utilizing Building Information Models (BIMs), but activity sequencing was still based on a set of static sequencing templates similar to the previous studies. Thus, existing studies have a limitation of being static and being dependent on the knowledge of experienced schedulers.

2.2. Daily work report data

DOTs, particularly resident engineers and site inspectors, collect a significant amount of data on highway projects, such as construction activities, labor hours, types of equipment used, equipment hours, and weather data. Currently, more than thirty DOTs in the U.S. are using digital DWR systems. Fig. 1 shows a screenshot of the AASHTOWare

SiteManager, which is the most popular DWR system among DOTs. Apart from being mainly used for payment and documentation purposes, DWR systems have potentials to be applied in other applications such as as-built schedule development and construction sequence determination. However, most SHAs have not benefited from those potential applications possibly because of the lack of knowledge on those potential benefits, enabling methodologies, and automation processes.

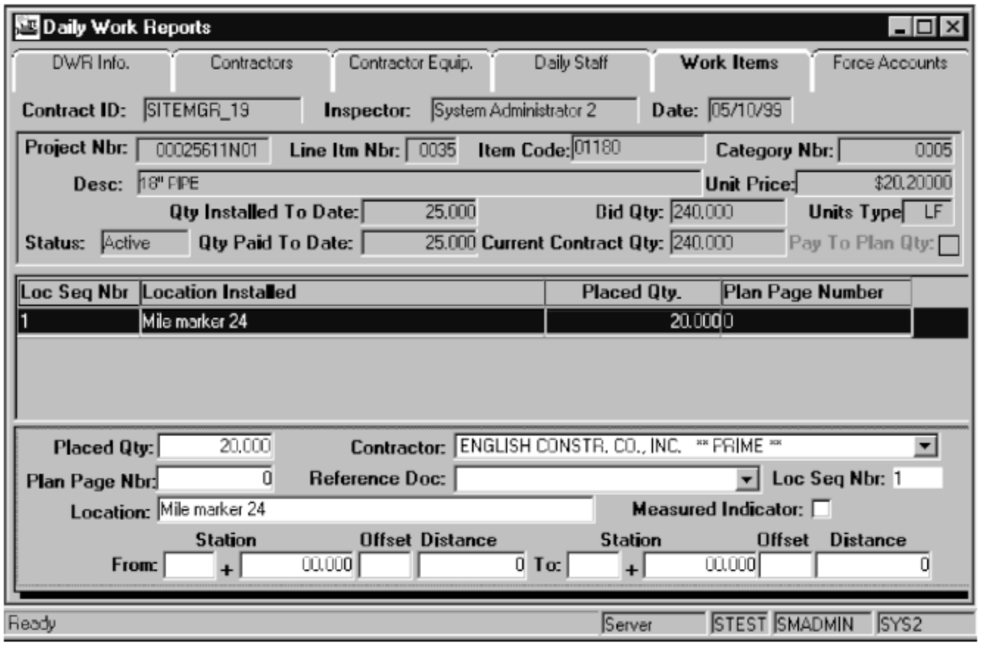

Fig. 1. AASHTOWare SiteManager screenshot

DWR data attributes are linked to separate work items. DOTs have developed an extensive list of work items that are primarily developed to facilitate the bidding process under the unit cost contracting method. Those work items are also used to develop a project schedule since they are independent work activities. DOTs have also developed and maintained specifications that provide a detailed description of each work item. For example, an item code “01180” in Fig. 1 indicates a work item “supply and installation of a mile marker.” A typical set of data attributes collected in DWR systems can be classified into six categories: general information, work activities, weather information, equipment, labor, and remarks. Among these six categories, the category of work activities was used for this study. The start dates of various activities can be extracted from the DWR system and then compared to identify the activity sequences for all historical projects. Those activity sequences can be identified using SPM algorithms.

2.3. Sequential pattern mining

A SPM algorithm can help identify interesting and hidden sequential patterns from a set of sequential data [9]. SPM algorithms have been used for various applications, such as DNA sequencing, medical treatment, consumer behavior, web access pattern, and stock market [9-11]. For example, if a consumer buys a cell phone on an e-commerce website, a case for the phone is likely to be recommended to the consumer.

In identifying the sequences of construction activities, as-built schedules of past projects can be analyzed using a SPM algorithm to help determine the sequences of activities for a new project. The Sequential Rules Common to Several Sequences (CMRules) is an open source algorithm that was used for this study [10]. The CMRules algorithm finds the sequential patterns that frequently appear in a sequence database and meet a minimum threshold value of confidence and support. For a rule in the form of $X \rightarrow Y$ (Activity Y happens after activity X happens), the confidence and support of the rule are defined as the following. The support of the rule is the number of sequences containing the activity X

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before activity *Y* in the sequence database [10]. The relative support of the rule is the support divided by the number of sequences in the sequence database [10]. The confidence of the rule is the ratio between the support and the number of sequences containing activity *X* [10].

3. Mining DWR data for detecting patterns of construction sequences

3.1. The proposed framework

This study proposes a framework for mining DWR data to detect patterns of construction sequences. The framework consists of six components: a) database preparation, b) project type selection c) data extraction, d) data transformation, and e) application of CMRules. First, DWR data was obtained from a current DWR system. As different types of projects may have different project sequencing, DWR data were separated based on project types. For a specific project type, relevant DWR data were selected. Start date information on each activity was extracted for each selected project. The data were then transformed into a format suitable for applying CMRules algorithm. CMRules identified and generated precedence relationships found in the DWR data.

3.2. Case study

A DWR database was obtained from a DOT in the Microsoft Access format. The database consisted of project information on over 2,000 projects from 2001 to 2014. Table 1 presents the top five project work types in terms of the total dollar amount. The project type "widening existing roadway" was the largest work type of all. This type includes the addition of passing lanes to improve traffic flow and road safety conditions. It also had a large number of projects. The work type "widening existing roadway" was then selected for illustrating the framework.

Table 1. Top five project work types in terms of the total dollar amount

Work type code	Work type	Total dollar amount	Number of projects
04	Widening existing roadway	1,799,474,488	204
19	Structures and approaches	864,634,085	231
07	Overlay	806,625,107	1264
06	Rehabilitation	605,243,188	49
16	Grading and structures	482,557,003	42

Since there were 204 projects (see Table 1), the sequence database had 204 sequences. Each sequence was the list of work items ordered sequentially based on the extracted start time information from the DWR system. The CMRules algorithm was applied to extract sequential patterns with various values of minimum relative support and confidence. The number of discovered patterns is shown in Table 2.

Table 2. Number of patterns obtained with different values of support and confidence

Relative support	Confidence		
	0.9	0.8	0.7
0.6	2	9	9
0.5	2	220	643
0.4	290	6,412	12,643

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Two of the results obtained from the analysis are presented below, including a simple one with two items (i.e., one-to-one relation) and a complex one with multiple items (many-to-many relation).

- (603001 -> 412001), 117, 0.78: This sequential rule indicates that the work item 603001 (maintenance of traffic) starts before the work item 412001 (cold milling asphalt pavement) in 117 projects (support). In the remaining projects, either one of those items is not included in the same project, or work item 412001 starts at the same time or before the item 603001. In 78% of the projects that include the work item 603001, the work item 412001 follows item 603001. Based on this sequential rule, if a new project includes the two items, the item 412001 would be recommended to start before the item 603001.
- (210201,303107,604023 ⇒ 624001,719001,719101), 112, 0.78: This many-to-many relationship includes three preceding work items followed by three work items. The three preceding items can start any time relative to each other; the three succeeding items can also start anytime relative to each other. The three preceding items are 210201 (unclassified excavation), 303107 (aggregate base course (class 7)), and 604023 (traffic drums); the three succeeding items are 624001 (solid sodding), 719001 (thermoplastic pavement marking, white-100), and 719101 (thermoplastic pavement marking, yellow-100). The three preceding items occurred before the succeeding items in 112 projects. Further, in 78% of the projects containing the preceding items, the succeeding items listed above start after the preceding items.

One-to-one sequences are visualized in a chart that can be used to visually extract the activity sequences for a new project (Fig. 2). The chart shows the work items as nodes and sequences by arrows similar to an activity precedence diagram. For example, regarding the first sequential rule discussed above, activity 603001 (maintenance of traffic) and activity 412001 (cold milling asphalt pavement) are highlighted in red in Fig. 2. The sequencing of two activities is indicated by the arrow connecting them (603001 ⇒ 412001). The widths of the arrow lines indicate the confidence of the sequence: the thicker the arrow line is, the higher the confidence is. Based on the activities of a new project, a relevant portion of this chart can be extracted visually to develop activity precedence diagram for the project.

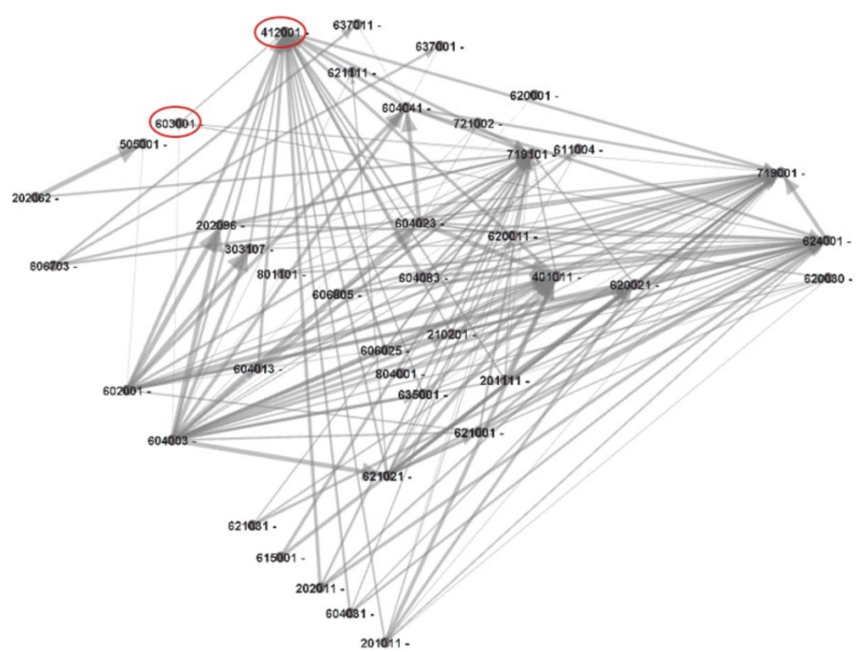

Fig. 3. Visualization of precedence relationships of activities

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4. Conclusion

While some industries have heavily utilized their data to obtain data-driven insights, the construction industry is lagging behind. This study developed a methodology to discover precedence relationships of activities based on DWR data collected by DOTs. Currently, state DOTs and contractors rely on engineers' experience to develop activity precedence diagram, which is very time consuming and complex. In this study, a novel framework based on the SPM algorithm was developed to automate such a process. This framework will aid schedulers in quickly identifying precedence relationships of activities, which is the most complicated part of schedule development. Thus, it provides guidance to the schedulers based on the historical data, minimizes their inputs, and improves their confidence. A dataset from a DOT was analyzed to illustrate the framework. The SPM algorithm generated 12,643 sequential rules that become a knowledge base to generate activity precedence diagram for new projects. However, this study only identified the start-to-start relationships among activities. Further research will be conducted to explore other relationship types such as finish-to-start and finish-to-finish relationships.

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Monitoring and Control Process of Construction Projects

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Abstract

Major causes of delays in construction projects are very common due to many factors caused by main projects stakeholders; client, consultant and contractor. Some of these factors are related to unclear objectives, risk identification processes, planning process, procurement process including tendering, construction process and supervision and lack of experience of performance measurement. Contractor's project managers of construction projects must be aware of work processes to avoid problem that may cause a delay of handing over the project. Some of these processes are project monitor and control. The research objective is to find out why process of project monitoring and control is major and important for project work progress and to determine the best practical techniques that can be utilized to track the work progress of construction project, and to make timely recommendations for required corrective action in response to any delays in the working detailed program. Monitoring project performance is a part of construction management processes that helps project manager to decide if the project can be delivered on time without any complain from the client. Project monitoring and control is important and essential for collecting the necessary information's that help projects managers to reviews progress regularly and help them to take any necessary action to avoid delays. The finding of the study shown the needs and actions required that must be considered by project managers to control internal process including essential techniques e.g. contractor selection criteria, operations of construction phases, control process, cost analysis, and labor and materials management. In the conclusion, internal control process is essential for contractor's project managers through appropriate and suitable effective utilization and adoption to the processes that must be identified at the beginning of the project.

Keywords: *Projects Managers, Monitoring and Control process, Risk Identification, Planning Process. Variances*

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1.0 General Introduction

There is big demand on construction projects due to continuous development of that industry all over the world which makes the process of construction regularly change from project to another, that's make project monitoring and control is essential for project managers and they must adopt suitable controlling methodologies and measures to keep projects schedules as planned. In addition to that the resources of project parties must also be monitored to ensure that project will be completed on time. very large range of parties involved in construction projects should be properly controlled to avoid delays. Now a day's project managers are using time, cost and quality and scope as a parameters to measure and control the progress of projects as confirmed by [1]. The reasons and principles of controlling the system of the work is to ensure that goals and objectives of project can be achieved within the agreed time.

Some other factors are considered as a factors attributes to project delays that are not properly monitored such as number of identified risks, number of variations, lack of skilled work force and late delivery of project materials. As per study and analysis the causes of delays in large building projects in Saudi Arabia and identified material related delays as the main cause of project delay [2]. Directors of construction contracting companies are always refer to the approved base line program as a part of monitoring and control process that they adopt where corrective will be considered to cover any occurred delay. The purpose of monitoring system is to check the continuity of work progress against the plan to help in taking any corrective action as confirmed by [3]. Special consideration and attention is required by the project team to complete major mile stones of project on time to ensure that project will be delivered without any delay subject to proper concentration in communication process, documentation process, inspection procedures, control process of risks and changes. The main reasons of the project delays are the changes of the contract document, inadequate supervision, late agreement with the Sub-Contractors and insufficient labor as confirmed by [4].

2.0 Literature review

In construction industry mega projects are the core business of any contracting organizations where project execution team managed by project manager become involved in work progress in day-to-day activities by focusing on the tasks that requires special monitor and control to avoid delays. This involvement leads the organization/ firm to seek the excellence in accomplishing the task/work activity on time as stated by[5]. Proper planning for work activities in advance are leading to project successful. Planning of activities and mile stones can be prepared by project team but must be monitored by the project managers through detailed process and tools where these tools must be available with the project team. Tools availability is critical factors in the productivity of construction team. Monitoring and control is related directly to project management and it is essential to assess and improve the project performance [6]. It helps project managers to evaluate the status of the project whether the objectives are being met. Monitoring can identify the operational constraints that affect the performance of the project. Some factors contributes to poor monitoring and control in construction projects like process of evaluating work, assessment process, and reporting actual work vs. planned, material management process and the level of accuracy of reported information that leads to a major delay in the project. Old process, manuals, materials management and poor control procedures are some factors attributes to lack of up-to-date, real- time information [7]. Contractors and consultants projects managers must have complete integrated system to control and monitor the project activities that must be agreed and approved by project stake holders during the planning phase of the project. The tools of monitoring could be automated or physical depending on the location, type, size of the project and the capability of the contractors firms. Automated and integrated project monitoring and control frame work that facilitate decision making by project managers to take corrective actions after deviation occur as stated by [8]. Reporting method is a part of communication process that should be approved at the beginning of the project by all stakeholders. If reporting method/plan is not sufficient, project can't be monitored and controlled properly. The quality of the data and information should be performed to the highest level of efficiency. Many projects are getting delayed because of the lack of accuracy of the reported progress that is not matching with the actual work where project manager's action is not reflecting the real action.

3.0 Purpose of projects controls

Monitoring and control applications in construction field are essential where these applications should be updated at the end of each project according to the reports of project managers and if they fail to do so regularly projects might get delayed because this is a part of their roles and responsibilities. A project may be delayed as a result of the direct action of major parties or of their failure to act especially if they have a duty to act [9].

Scheduling and planning techniques in construction projects are not yet considered as a final practical process with respect to the provided information about the activities that has to be planned where some schedulers and planners are thinking to modify some changes in the flow process during the work progress. Scheduling of the project requires the project manager to identify two initial aspects of project activities. First, there are some of the activities which are required to be done in series and in orderly manner, whereas others can be done in the same time [10]. Project managers and planners focus on information recorded in guidelines as a general common method to collect information during project execution phases while the reported information will remain incomplete. It is necessary to establish an effective integrated process to achieve project monitoring and control system that helps of enhancing project performance to reduce potential risks and delays. In projects, projects managers, schedulers and planners must recognize that efficiency of skilled manpower in sites can also be monitored where productivity can be improved. A framework for semi-automated project monitoring and control has been proposed where the collected data can be incorporated taking into account the impact of productivity of existing deviations from the planned performance and the controlling actions proposed to deal with these deviations [11]. Process of monitoring and control in construction projects keep an eye on and focus in all responsibilities of developing metrics to ensure that the work progress of the project is within the scope and the budget so that unexpected potential problems can be reduced. Corrective action is one of the major important tasks that project managers must take based on the comparison between the planned progresses and actual mainly if they determine the deviation part that caused a problem. Project control are the data gathering and analytical process used by the project team through the communication of information transmitted based on proper facilities and by a designed templates that complies with the nature of the project to assist the project leaders in decision making. The project members should be provided with the best facilities so that they can work in a manner in which the project can be executed without a delay as stated by [12]. A part of project manager responsibilities is comparing the planned results with the actual to ensure that the project activities are in progress without a delay, a corrective action can be considered by project manager for any deviation. Identifying the reasons of problems that caused the deviations should be recorded a s a learned lesson. Project managers are concentrating on important points through monitoring and controlling to maintain progress, some of these points are reviewing and tracking project progress, forecasting completion date of some activities, updated schedule, actual cost up to date, potential records of risks and change management plan. This requires a pro-active approach and full commitment by the project team and project manager. It is important to realize that scheduling requires a pro-active approach to ensure all relevant inputs are captured and there is a good understanding of the execution assumption and schedule risk [13]. The accuracy of the data collection process can be influenced and maintained by accomplishment of certain practical actions through committed project team. They ‘’project team” who presents client, consultant and contractor must agree at the beginning of the project about recording system of data related to monitoring and control of activities which is a part of construction process. The sources of delays caused by Client, Consultants, Contractors, Sub-Contractors and those which are not caused by these parties to the design and data of construction process[14]. It is necessary that project team members must prepare a mechanism to maintain the value of the data during mobilization period of the project. The data must be clear, readable and measurable.

4.0 Aims and Objectives of Study

Aim of that research is focused on the implementation process of practices of monitoring and control in construction projects and its effect on the completion of the project on time. Assessing the impacts of failing of utilization the tools of monitoring and control has been investigated in this research to find out the necessity of these factors that are essential to be adopted by projects stakeholders mainly projects managers and planners.

5.0 Methodology

Full inclusive methods have been adopted in this research to accomplish and carry out the purpose of that study e.g. literature review, questionnaires and data analysis. This section explains the process and methods that helped the author to come out with necessary required analysis to conclude the study.

5.1 Research Approach

Two approaches of data collection, qualitative and quantitative analysis has been approached to help the author developing proper analysis of the collected data through a detailed methodology.

5.2 Quantitative and qualitative analysis

Qquantitative analysis is the assessment of data collected by means of survey techniques through statistical methods with the purpose of ensuring that the collected data are both reliable. For the qualitative, analysis qualitative approach to research as the study of things in their natural setting, attempting to make sense of, or to interpret, phenomena in terms of the meanings people bring to them [15]

5.3 Data Collection

Primary and secondary date is the main types of data that has been collected by the researcher with the intention of developing the results that he needs. Collected date has been dealt with in turn in order to explain its necessity for that research. Author has generated primary data based on the combination of finding the analysis of literature review and other different sources that has been approached through meetings, interviews and questionnaires.

6.0 Design of questionnaire survey and data analysis

Questionnaire surveys are one of the methods to gather the information's /data. Questionnaires are developed to collect the required information's to identify level of implications of processes that adopted by project managers and his team to monitor and control progress of the work at very effective method. Project managers requested to answer questions listed in the questionnaire form. Form of data collection is the most widely used source of primary research amongst researcher as it provided access to a wide range of professionals which would normally be beyond the reach of most researchers as stated by [16].

Apart of project manager responsibilities is to monitor, follow and control the construction activities of the project where a list of major points are listed in table 1, where survey is prepared to evaluate the perceptions of project managers to the applications of internal control process. The questionnaire is developed based on five important processes that have been founded in the literature review of that study. Participants requested to identify the level of meaning of each process which is:-

- Developing base line for assessing project performance
- Quantifications of project variances

- Measuring potential impacts of variances on baseline and cost of the project.
- Assessment of proposed corrective actions in case of occurred problems
- Evaluating the impact of the associated works resulted from the implemented action on the project

Table 1. Several Important actions to be considered by project manager and his team

SN	Question/process	Validity	Means	Rendering	Standard deviation
1	Developing base line for assessing project performance	100	2.98	57%	1.630
2	Quantifications of project variances	100	3.25	59%	1.992
3	Measuring potential impacts of variances on baseline and cost of the project.	100	3.95	68%	2.711
4	Assessment of proposed corrective actions in case of occurred problems	100	3.09	58%	1.859
5	Evaluating the impact of the associated works resulted from the implemented action on the project	100	2.40	52%	1.426

7.0 Data analysis and findings

One hundred project managers and schedulers working in five big contracting organizations responsible for construction projects requested to fill hundred distributed questionnaires. In each organization project managers were requested to respond to ten questionnaires and schedulers were requested to fill other ten forms. Participants have confirmed that most of the listed tasks are a part of their daily tasks. They regularly are informed about issues, potential problems and potential risks through regular reports submitted to them by schedulers and project engineers. Many of them has reported that they instruct some members of the project team to follow up with issues related to problems because they always busy in meetings with projects stakeholders to finalize all pending subjects related to work progress and to continue positive contractual relationship with them for future projects. Based on calculated results recoded in table 1, the standard deviations, calculated frequencies, means for providing and analyzed regression founded on the estimated relationship among the variables the analysis has been prepared and developed. The rationale of the collecting and analyzing the data is to observe the level of the obligation of project managers and their schedulers in monitoring and control process and to determine the impact of ignoring these implications including best practices to ensure that projects are monitored and controlled.

It is noted for item no. 1 that the base line development, the value of standard deviation is 1.630, means that the variables are notably increase across the mean 2.98. As rendered based on Table I that 57 % concerned about developing the baseline program covering all activities. Quantifications of project variances which is a part of the important tasks of projects managers, the value of standard deviation is 1.992 showing that the results are greatly spread across the mean value of 3.25**,** suggests that around 59 % of the respondents confirmed that projects managers are monitoring but not to the required level because they have some other tasks to follow with other projects stakeholders members. Regarding item no. 3 recorded in table 1 which is measuring potential impacts of variances on baseline and cost of the project. it is noted that the standard value deviation of this factor is 2.711, shows the results spreading across the mean value of 3.95 as where 68 % of the respondents stated that measuring potential impacts of variances is always checked by the project team. Regarding the assessment of proposed corrective actions in case of occurred problems the results are spread across mean of 3.09 as shown in Table I and standard deviation is 1.859 where 58 % of respondents reported that assessment of corrective actions are considered by schedulers through the software's programs. They reported that it is project manager responsibility to find out the financial impacts of any corrective action they are taken. For the means of the last item of table 1 that is evaluating the impact of the associated works resulted from the implemented action on the project is 2.40 and the standard deviation is 1.426 which indicates that 52% of the participants evaluating the impact of associated works of implemented actions.

8.0 Conclusion:

Process of project monitoring and control is one of the important tasks that project manager must consider at the beginning of any project. Project team should be familiar with the standards of the application process of monitor and control where results of these applications must be presented on weekly /monthly reports they prepare for projects managers. He/ she must directly reporting to the higher management on regular basis explaining the status of the project where project variances, potential issues, deviations problems and required actions are a part of the report

Assessment of measuring cost performance to ensure that the planned budget is adequate and enough to deliver the project on time is essential and measuring the schedule performance to ensure that the planned schedule and dates can be accomplished. Moving ahead or proceeding in advance for required necessary actions of variances exceeds the planned duration by 15-25% percentage is essential where project team must always plan for that action. Any deviation from the base line should be considered as of the highest priorities where project manager must take necessary action to control it. Submitting a change request with full cost associated report for any required action is a part of preventive action to reduce cost and causes of change orders considering that changes can be implemented in a performed integrated manner to come out with an appropriate evaluation for the changes impacts to reduce risks of changes. Follow-up approved implementation process of quality plan helps the project manager and his team to monitor quality assurance and control till project is completed. Adopting risk module analysis help project team controlling all potential and anticipated risks during the work progress. Monitoring the productivity and resources utilization of each project activities can be monitored by the project team to ensure that mile stones can be completed on time.

9.0 Recommendation:

Successful implementation of process of project monitoring and control attributes to the success of projects. Adopting these processes validate the performance of the project and solve any potential problem faced that may affect time, cost and quality or other problems faced to follow the planned schedule. Proper system of monitoring and control must be established at the beginning where that system can be implemented and monitored through the life of the project. This can be achieved through the experienced projects managers and committed project team who should be familiar with these process /system of control of the project which depends upon the kind, value, size and location of the project itself. Regular assessment of information e.g. variances must be directed in successively at greater level of details to catch the problems in the project and how they affect the schedule. Assigning committed team members working in the project to follow-up the recommended actions of recovery plans and to monitor the required actions to close the identified risks is essential where that team must report directly to the project manger and must be supervised by him as well.

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Ontology assisted collaboration sessions on 4D BIM

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Abstract

Stakeholders use 4D modelling during construction to coordinate project data and collaborate effectively. The collaborative sessions between project stakeholders have a complex dynamic. This research was conducted under the scope of the 4DCollab project, which aims to improve 4D BIM supported Synchronous Collaboration Sessions (SCS) by adopting a user-centric approach, whilst considering specific 4D use-case information requirements. Following several experimental SCS, an initial ontology model was developed. This model offers a holistic view of the dynamics between the following main concepts: the meeting itself (session), its participants (users), the 4D BIM model and the collaboration devices used for decision-making. Several existing schemas within the BIM domain were identified and considered for the definition of the proposed ontology, re-using several already validated concepts. The 4DCollab ontology is introduced following a rigorous design methodology. Its applications, limitations and future work are also outlined and discussed.

Keywords: 4D; BIM;Ontology; Decision-making; Collaboration; Linked Data; IfcOwl ;

1. Introduction and research scope

1.1. Planning with 4D BIM

BIM processes and models are continuously present from concept design to facility management. The entire process reaches its information apex during the pre-construction and construction stages, where all stakeholder models converge in order to coordinate, collaborate and facilitate decision-making. Considering the nBIM paradigm [1], the construction stage is mainly associated with 4D BIM, where the connection between the 3D BIM and the time management information is carried out. The 4D is a digital representation of the construction site, where several use-cases are applied [2] [3]. These range from construction logistics and safety management to modern site monitoring technologies which employ mobile devices, laser scanners and drones. These processes bring several heterogeneous sources of information to the decision-making, in various formats and with different levels of semantics. This research was developed under the 4DCollab project [4], which aims to deliver a novel, more holistic and collaborative 4D

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system, while considering a user-centric approach. The scope of this article is narrowed down to the ontology representation of Synchronous Collaboration Sessions (SCS), within the context of 4D BIM and Natural User Interface (NUI) devices. The article introduces the research basis on which the 4DCollab ontology was created, a presentation of its main concepts and also its alignments with the IFC schema.

1.2. Synchronous collaboration using natural user interfaces

The interfaces of 4D BIM tools are traditionally aimed at trained CAD professionals. Additionally, these tools are not designed for collaborative devices. To overcome these limitations, our research explores the use of NUI to offer improved interaction between users and the 4D model during SCS. We define a SCS as the setting in which project stakeholders meet around a digital table, represented by a multi-touch collaborative device [5], with their digital documents that are brought in dynamically, according to meeting scope and needs. Experiments conducted in the past based on this setting[6], revealed several requirements in terms of: 1) user-centric interface features and 2) relevant project data. The heterogeneous project data varies from 3D geometry (IFC, laser scans, etc.), planning to site change order forms, which is used within the context of 4D modelling. However, these data sources are not semantically connected, hindering collaboration as a result. SCS should allow a semantically rich, knowledge-driven environment which would place model data at the fingertips of the end-users.

1.3. Linked data paradigm and ontology representations

The semantic web linked data paradigm allows to connect BIM with the IoT and AI agents, thus paving the way to automation, smart construction and digital twins. This study aims to benefit from linked construction data and to model the context of 4D BIM-based SCS. Although the IFC schema can be used to accurately represent 4D models, as it already includes sophisticated concepts for time and scheduling, it lacks in concepts related to inter-user collaboration and their decision-making processes. Additionally, the use of the IFC schema within the 4D domain is currently limited to research [7] with a vast majority of concepts not implemented nor used in practice.

The emergence of IfcOwl [8] has seen several implementations within a semantic web context [9]. The ontology representation of the BIM not only bypasses the interoperability problem, but also offers a more robust foundation to store and to link data on the web. Most importantly, it allows a more comprehensive conceptual and consequently digital representation of real-world ‘things’, from simple semantics to knowledge.

2. 4DCollab ontology design methodology

A rigorous experiment focused methodology was employed, based on observations of conducted from seven SCS, and on the feedback of the AEC professionals involved. In order to ensure that validated concepts from adjacent knowledge domains are re-used, existing schemas and ontologies were surveyed, and their concepts considered (section 3). The ontology itself (section 4) was set to follow certain objectives in order to focus its use, as outlined in Figure 1. It is acknowledged that the process of constructing the 4DCollab ontology is iterative, and thus some concepts and their relationships are expected to change after further testing in via real use-cases.

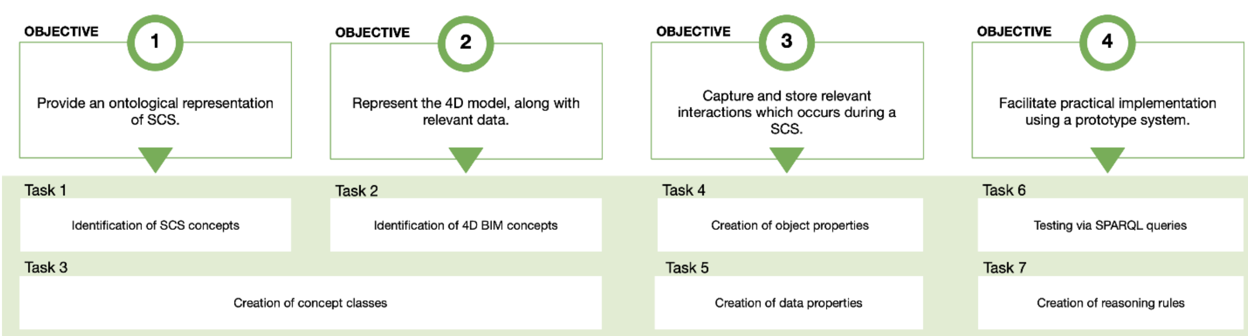

Figure 1. Methodology employed for the design and testing of 4DCollab ontology

3. Existing ontologies, schemas and workflows

Several open schemas relevant to the BIM, collaboration and project management domains were considered throughout the 4DCollab ontology construction (Table 1). Concepts related to 3D and 4D models, Time, Collaboration, Level of Detail/Development (LOD) and Resource (document, materials, etc.) were included.

Table 1. Identified relevant ontologies classified by major concepts

Ontology/Schema	REF	Concept fields					
		3D	Time	4D	Collaboration	Resource	LOD
IFC schema / IfcOwl ontology	[8]	✓	✓	✓		✓	
PROMONT ontology	[14]		✓		✓	✓	
Microsoft Project schema	[11]		✓			✓	
W3C Time Ontology	[12]		✓				
Collaboration Ontology (CO)	[13]				✓		
Ontology for Property Management (OPM)	[15]						✓
Building Topology Ontology (BOT)	[10]	✓					

The majority of schema models outlined in Table 1 are heavily focused on specific domains, with relatively small scopes, and are therefore relevant to only one or two field concepts. The PROMONT ontology on the other hand, represents collaboration and project management concepts in a generic field, which could be re-used to describe relationships between tasks and time management. However, its remoteness limits its usability.

The IFC schema and its ontology version are the most suitable candidates for representing the 3/4D BIM. Thus, IfcOwl can be seen as a source of model information, while ensuring interoperability with other industry tools and formats. However, the complexity and heavy structure of the IFC schema and consequently IfcOwl make it a less than optimal ontology to be used in practice, especially where reasoning is concerned. This has been a subject of research in its own right and as a response, the scientific community within the AEC/FM industry has come up with several smaller and more modular ontologies, such as BOT or OPM , most of which are aligned with IfcOwl. However, none of these newer ontology models have within scope the synchronous collaboration between users, and their interactions with various digital documents and artefacts, which were outlined as part of this research in [2].

Another important aspect that was taken into account was the collaborative meeting workflow. Existing guidance on 4D BIM modelling [16] describes the collaborative process of combining the 3D with the scheduling information, but not in a synchronous context. Additionally, various artefacts are in use during SCS, which are brought to the table in an ad-hoc manner. Therefore, one of the aims of the 4DCollab ontology was to provide the necessary relationships between these artefacts, the BIM, the actors and any other relevant ad-hoc external resources which are required in the decision-making process.

4. 4DCollab ontology

Considering the objectives in Figure 1 from section 2, the first two refer to representing ‘things’ which are both virtual (the BIM) and real (the site, the actors, the devices), thus capturing an environment in which people use the 4D model to make changes and take decisions. The third is more concerned with providing an intelligent, knowledge-driven environment where the context of each session is captured for future reference and analysis, adding value to knowledge management and data analytics. The final objective is to test and validate the ontology, which would further ensure its efficacy and completeness.

The conjunction of project aims and the ontology objectives were used to design an initial 4DCollab ontology, presented in Figure 2. The main concepts are presented below, following several competency questions which were used to logically guide the scope of the ontology. The use of ‘competency questions’ is a formal way to assess that an ontology meets certain objectives and is capable of providing an answer to the problem it is applied to.

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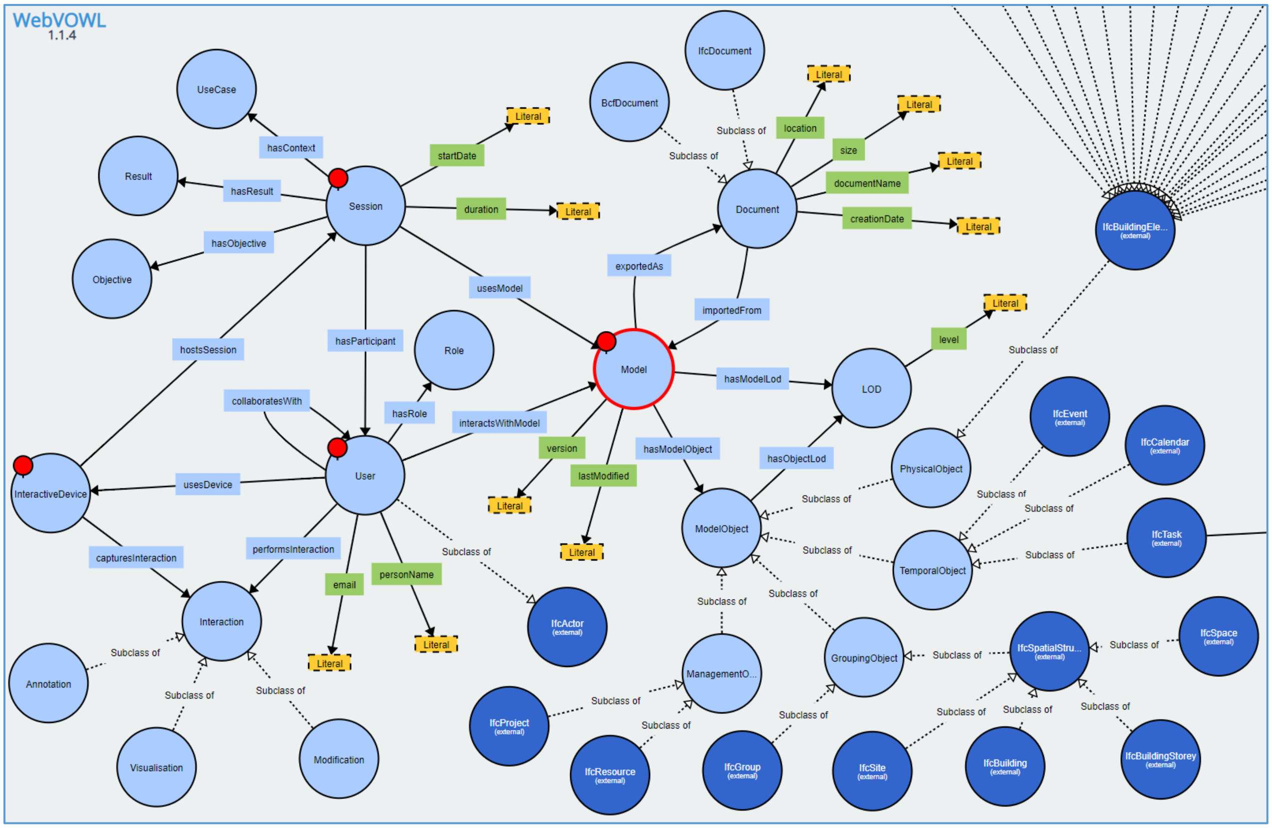

Figure 2. Overview of the 4DCollab ontology main classes with their object and data properties

4.1. Main classes

The core 4DCollab concepts were outlined by posing the following competency question:

"What type of 'things' does a synchronous collaborative session have?"

These concepts were broadly confined within the things around the discussion table:

- *Session* – the abstract concept referring to a synchronous collaborative meeting, at a certain point in time; Each session is related to a specific *Model* (the 4D BIM), and has specific *Objectives* at the beginning and *Results* at the end. The context of each session is dictated by the *UseCase*, referring to the 4D use-cases [2] [3] which filters the necessary model data for visualization and interactions.
- *Model* – the abstraction of the 4D model which is the subject of debate during a session, which itself comprises of 4D BIM objects, which are *importedFrom* documents before a session and exported at the end, as *Results*;
- *User* – representing people around the table which participate in collaborative meeting. Each *User* has a specific *Role* [2], and his *Interactions* with the NUI is captured by the device used to host the *Session*;
- *InteractiveDevice* – a physical collaborative device which allows users to visualize, manipulate and update the model using natural user interfaces.

4.2. The 4D Model

A pivotal element within the meeting is the 4D model itself and its dependent digital objects and documents which are used by the users around the table. The primary competency question posed was:

"What does the 4D model have to provide during a collaborative meeting?"

The *Model* class abstracts the interactions between 4D modelling objects and documents which are related to SCS. The difference between *Model* and *Document* is that the latter represents a static deliverable with low semantics, whereas the *Model* and its *ModelObjects* represent the fully semantic BIM objects which can be dynamically loaded and manipulated during the meeting. A good example of this is to compare a drawing document, which can only be visualized and annotated to a 3D model document file which can be interacted with at an object level.

The specific *ModelObjects* are further divided into several sub-classes (*TemporalObject*, *PhysicalObject*, *GroupingObject and ManagementObject*) and rely heavily on imported concepts from IfcOwl to correctly represent the 4D model according to common industry practice. *PhysicalObject* conceptualises all the elements within the BIM which have a physical representation in reality, therefore including the entire set of *IfcBuildingElement* class within IfcOwl. This can be summarised as the geometric model plus all the attached properties and its semantics. *TemporalObject* refers to concepts which are related to time and therefore used to describe the scheduling of the model, including in this case IfcOwl classes such as *IfcEvent* and *IfcTask* with all their attached concepts. *GroupingObjects* refer to the abstract collections and building shapes, consisting of *IfcSpatialStructure* and *IfcGroup*. They act as containers of other objects, being used to refer to specific zones, areas, spaces and levels within a building, to specific groups of scheduling tasks or a hybrid combination of objects. This ensures more dynamic grouping definitions, according to *User* needs.

4.3. The data properties

To align with the third objective, the 4DCollab ontology stores all relevant data about the model and the sessions via the data properties, as shown in green in Figure 2. These are used to create the context of the model, each session and its participants over time. At the model level, the data properties depend on the imported IFC classes, of which not all are shown Figure 2. However, the presence of Model related data will be managed using the Level of Development (*LOD*). Tts implementation will have to rely on reasoning rules to consistently check the presence/absence of data. In return, this will allow the monitoring of the model changes in accordance to the meeting objectives and results and make a connection between LOD progression not just at a 3D level, but at a 4D BIM level. These tools enable the capability of knowledge storage, and retrieval, and a means to use AI and data analytics to further optimize and replicate a design decision when it comes to 4D planning.

4.4. Example model queries

Based on the constructed ontology model, several queries are used in Table 2 to display their application for the various objectives previously envisaged.

Table 2. Example SPARQL queries and their equivalent natural language questions

No	Scope	Queries
1	Meeting preparation	*"What are the imported documents for the current session?"* SELECT ?session ?doc WHERE { ?model 4dOnto:importedFrom ?doc . ?session 4dOnto:usesModel ?model . ?session 4dOnto:startDate ?date . FILTER (?date = "29/03/2019") }
2	Model filtering	*"What are the physical model objects and their IFC IDs available within the model?"* SELECT ?object ?id WHERE { ?object rdf:type ?class . ?object ifcowl:globalIf_IfcRoot ?guid. ?guid express:hasString ?id. FILTER (?class = 4dOnto:PhysicalObject) }
3	Interaction analysis	*"Which are the annotations performed during the last session?"* SELECT ?user ?annotation ?session WHERE { ?session 4dOnto:hasParticipant ?user . ?user 4dOnto:performsInteraction ?annotation . ?session 4dOnto:startDate ?date FILTER (?date = "16/06/2016") }

Each SPARQL query during live SCS would represent the needs of the collaborative device end-users. The model data and history stored within the ontology graph database would be queried ad-hoc in order to satisfy session information requirements. Simpler questions posed are limited by the availability of information (which should be present and valid), while more complex questions would require the implementation of reasoning rules.

5. Limitations and future work

Due to the iterative process employed for the ontology design, its structure and classes are expected to change after practical implementation and testing. The current focus is set on re-using IfcOwl concepts, due to the scale and the interoperability the IFC schema provides. However, this can be easily extended to other relevant ontologies and domains as was shown in section 3, or any source of information on the web for enrichment of user experience.

Future work will test the ontology implementation on a new information system (under development), where it would act as the semantic information layer to connect the heterogeneous data during SCS. This would in return validate the ontology and assess its completeness.

Another perceived use to be explored is the connection of the NUI with natural language processing, whereby the interactive devices are able to understand and communicate with people around the collaborative device via vocal commands. The 4DCollab ontology would provide a semantic layer to correctly search for vocally requested data.

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Resource Levelling with Float Consumption Rate

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Abstract

The use of an appropriate scheduling method is not sufficient in constructing a reliable schedule. The management of resources is as important as the scheduling method. Inefficiency in managing resources may bring about severe delays as well as cost overruns caused by resource shortages in some cases and/or idle resources in others. Therefore, resources should be utilized efficiently in order to prevent project failures. Resource leveling is one of the approaches that are used for the management of resources. The goal of resource leveling is to minimize fluctuations, peaks and valleys in resource utilization without changing the completion time of a project and the number of resources required. Although the main principle behind traditional resource leveling is achieving an even flow of resources while the original project duration remains unchanged, it is possible to develop a more efficient model that discriminates among the activities that are selected for participation in resource leveling. For this purpose, a model was developed that considers the float consumption rates of activities. The float consumption rate is the percentage that is set to determine the maximum amount of float which will be consumed to shift the start time of the activity. The proposed model allows the scheduler to assign float consumption rates to each activity that can be used during the resource leveling procedure. When the required information is input, the proposed model automatically changes the required daily resources as it shifts the non-critical activities along their available total float times. The proposed model is expected to minimize the likelihood of severe delay and cost overrun. The model is demonstrated on an illustrative example by constructing a network and its resource utilization histograms.

Keywords: Resource management, resource leveling, float consumption rate, scheduling.

1. Introduction

In real life, the limited resources may be required by several activities in construction projects. This may lead to shortages and idleness, which in turn may bring about severe delays. Therefore, efficient utilization of resources may help to prevent project failures. There are two common approaches for management of resources; (1) resource allocation, and (2) resource leveling. Resource allocation attempts to minimize project duration according to the constraints on resources. On the contrary, the main goal of resource levelling is to minimize fluctuations in resource utilization without changing the completion time of a project and the number of resources required [1-5]. In order to achieve this goal, the start times of the non-critical activities are shifted along their available float times [6].

There are several studies focus on resource management in networks constructed by critical path method (CPM) [2, 7, 8], but only some has considered the impact of float loss on schedule flexibility [9, 10]. Even though these studies

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focus on trade-offs between resource leveling and schedule flexibility, the impact of float consumption on schedule flexibility is evaluated by float loss cost. The study presented in this paper was initiated as a response to the absence of a model that provides a tool for adjusting float consumption rates without need of float loss cost data. Therefore, the main objective of this study is to develop a resource leveling model in which a scheduler can assign float consumption rates to each activity in order to achieve a balance in resource utilization and schedule flexibility. The model was demonstrated on an illustrative network from the literature. The following tasks were performed in the case study (1) running the scheduling module of the model in order to calculate the total project duration, the start/finish times and floats of activities through basic critical path method procedures, (2) determining the particular activities that are eligible for resource leveling, (3) running the resource leveling module of the model, and (4) generating and comparing the resource utilization histograms before and after resource leveling.

2. The Proposed Resource Leveling Model

The resource leveling model was developed through Visual Basic Programming Language integrated with Microsoft (MS) Excel. An Excel-based approach was selected because it is reliable and transparent because one can observe the performance of the program in every step of the process.

The first step of the model design is the development of the module that performs basic calculations to set up a CPM schedule. In this module, the scheduler inputs information about activity names or activity codes, the precedence relationships, duration, and the number of resources used in each activity. After the scheduler inputs the necessary information, the module automatically calculates the total project duration, the start/finish times and floats of activities in the network. Once the start/finish times and floats of all activities are determined, an initial CPM network and its resource histogram can be plotted that uses the specified resources in each activity.

The second module of the model deals with resource leveling. Four consecutive steps are followed in the development of the resource leveling module, namely: (1) defining the MS Excel cells that represent the variables; (2) specifying the constraints; (3) defining the objective function; and (4) assigning float consumption rates to each activity. The first step involves defining the MS Excel cells that represent the variables, which are the start times of the noncritical activities. The activities that have a total float are identified as the activities that are eligible for resource leveling. Total float is the time by which the completion of an activity can be delayed beyond its earliest finish time.

The constraints for the resource leveling specified in the second step. The first constraint ensures that the start times of these noncritical activities may assume only integer values within the limitations of their total floats as expressed in Eqn (1). If an activity is eligible for resource leveling, then the start time of that activity is shifted forward or backward by using the total float. However, total float is shared with other non-critical activities on the same path in a network. If a scheduler ignores the sharing of total floats, then this may lead to violation of precedence relationships. Therefore, when a total float of an activity is used for shifting its start time, the resource leveling module must also check that the precedence relationships between network activities are not violated. The last constraint prevents violating the precedence relationships between network activities by recalculating the start/finish times and floats of activities after using float of activities. Thus, shifting the start times of the noncritical activities within the limitations of their total floats does not violate the precedence relationships in the network.

$$Early\ start\ time \leq Start\ time\ of\ the\ activity \leq Early\ start\ time + Total\ float \tag{1}$$

The objective function for resource leveling process is determined in the third step. Various objective functions are used in previous studies to perform resource leveling [12, 13]. Even though different objective functions have different mathematical formulations, all of them have a common objective of providing a smoother resource distribution. In this study, the minimization of the sum of the absolute deviations between daily resource requirements and the average resource requirement is selected as the objective function. It is one of the most commonly used objective functions for resource leveling [2, 4, 11, 12]. An MS Excel cell is set up to represent the objective function in Eq. (2)

$$Z = min \sum_{i=1}^{T} |R_i - A_{rr}| \tag{2}$$

where *min*= minimize, i =day under consideration, T = the duration of the project, R_i= resources required on day i, A_{rr}= average resource usage.

Determining the preferred float consumption rate is the final step in the development of the resource leveling module. The float consumption rate is the percentage that is set to determine the maximum amount of float which will be consumed to shift the start time of the activity. The resource leveling module allows a scheduler to assign float consumption rates to each activity according to a preferred criterion. For example, a scheduler may pursue a strategy implying that more attention should be paid to complex activities because it is more likely to have a delay on these activities due their complexity. Therefore, in order to prevent delays in these activities, a more complex activity deserves a lower float consumption rate in leveling compared with a less complex activity. In sum, one of the most important advantages of the proposed model is that it provides flexibility to a scheduler to pursue different trade-off strategies in resource leveling.

When the required information is input, the proposed model automatically changes the required daily resources as it shifts the start times of noncritical activities. It should be noted that the start times of noncritical activities are shifted along their maximum amount of float determined by float consumption rates. Thus, the model finds the optimum start times of activities to level resource usage. It also automatically generates the schedule and the resource histograms after resource leveling. The total project duration, the precedence relationships between activities, and the duration of an activity in any unit remain unchanged after resource leveling. On the other hand, the proposed model has a limitation too in that it does not consider the point-to-point relations which are claimed to be better from traditional precedence relationships of CPM [14]. Assessing the point-to-point relations, different objective functions for resource leveling and multiple resources would be a potential improvement for this model.

3. Case Study

The illustration of the proposed model can be best demonstrated by an example. A network from the literature is used for this purpose [1, 15]. It consists of eleven activities and requires a single type of resource. Even though other resources may be necessary for completing the activities, in this study, only a single resource type was considered for demonstration purposes. The information for each activity concerning precedence relationships, durations (in days), and daily resource requirements is shown in Figure 1. When the scheduling module of the model is run, early start/finish times, early/late finish times, and total floats of activities are calculated (Figure 1). The schedule and resource histogram before resource leveling are presented in Figure 1 and 2. The sum of absolute values of the deviations between resource usage on any day and the average resource usage is 69 for the initial resource histogram (Figure 2).

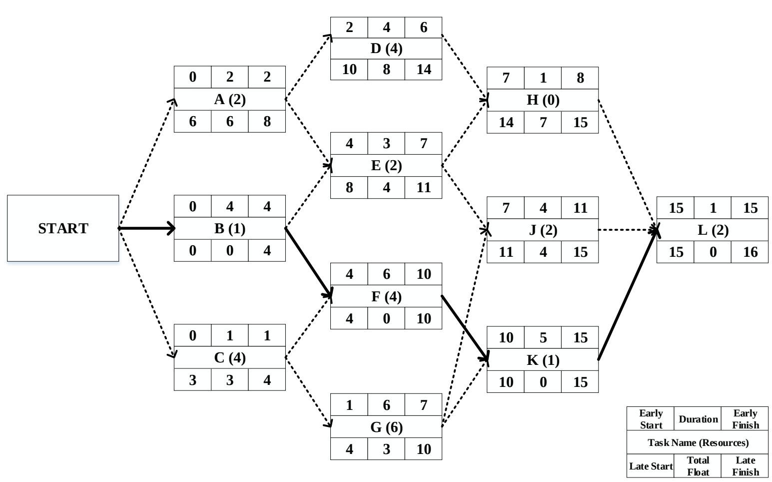

Fig. 1. Network for case study

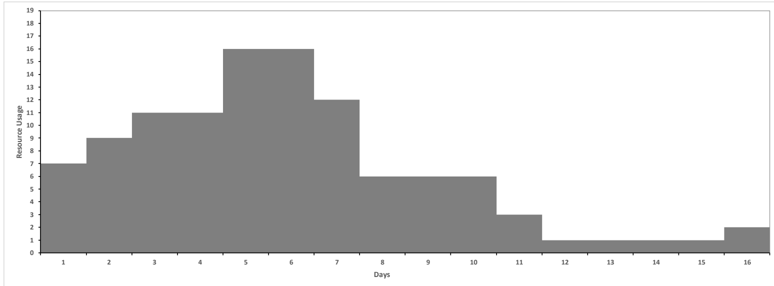

Fig. 2. Resource usage histogram before resource leveling

After plotting the initial schedule and resource histogram, non-critical activities are automatically identified by the scheduling module. Before running the resource leveling module, the model asks for assigning a float consumption rate to these activities. In resource leveling module, the scheduler is allowed to assign float consumption rates to each activity according to a preferred criterion. In this example, the maximum rate is set as 90% for the float consumption of the activities that are scheduled to start before and on the 8th day. In other words, setting a float consumption of 90% implies that an activity that is scheduled to start in the first half of the project cannot consume more than 90% of its float in resource leveling. On the other hand, a lower maximum float consumption rate (i.e., 50%) is assigned to the activities that are scheduled to start after the 8th day. This float consumption rate implies that an activity that is schedule to start in the second half of the project cannot consume more than 50% of its float in resource leveling. The preferred trade-off strategy intends to provide a flexibility to the activities scheduled to be completed in the second half of the project. Providing that flexibility may help in preventing severe delays in the project completion which in return improve the project performance.

Once all the parameters are set resource leveling module was run. Resource leveling was made within the completion time of the project (i.e.,16 days) and by making sure that the interdependencies are not violated. The schedule and resource histogram generated after resource leveling are presented in Figure 3 and 4. After resource leveling, it was observed that the sum of the absolute deviations between daily resource usage and average resource usage is reduced from 69 to 35, which corresponds to an improvement of 49% (Table 1). As a result, it can be stated that one of the most important benefits of the proposed model is that it provides a smoother resource histogram while maintaining the schedule flexibility. It should be noted that if this trade-off strategy is ignored, the resource histogram could have been smoother, but schedule flexibility would have been suffered. Implying this trade-off strategy provided schedule flexibility because none of the activities consumed their all available floats.

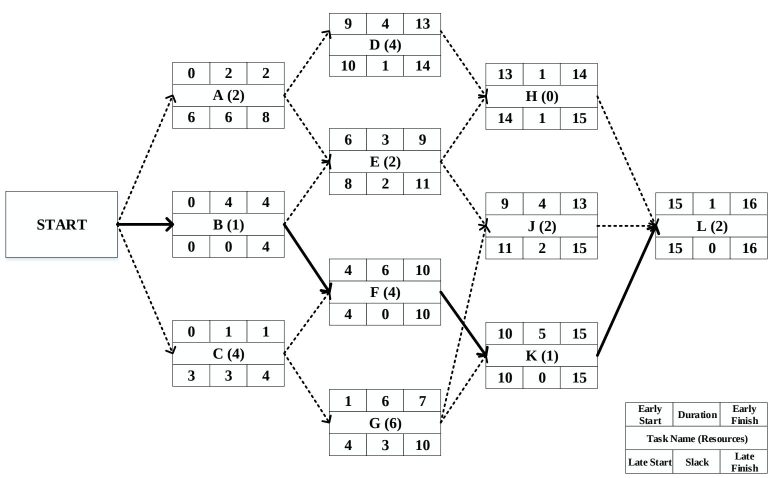

Fig. 3. Network after resource leveling with a float consumption rate of 90% and 50%

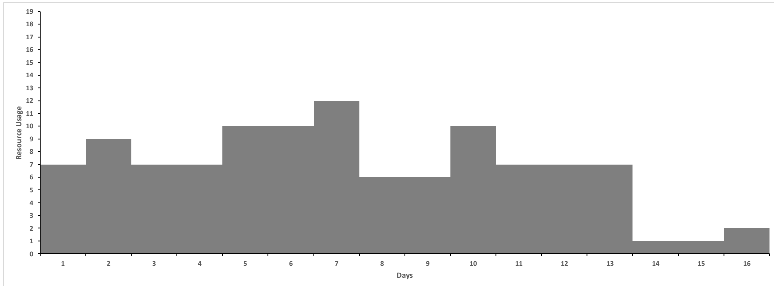

Fig. 4. Resource histogram after leveling with a float consumption rate of 90% and 50%

The model was also run with a float consumption rate of 100% for all activities in the network. Using a float consumption rate of 100% is a trade-off strategy that attaches more importance to resource utilization rather than schedule flexibility (Figure 5). Indeed, after the resource leveling, it was observed that the model generated a better resource utilization histogram compared to the one obtained by assigning a lower float consumption rate to the activities in the network.

Table 1. Percentages of improvement

	Number of noncritical activities	$Z = min\sum_{i=1}^{T}\lvert R_i - A_{rr}\rvert$	**Improvement percentage (%)**
Before leveling	7	69	-
After leveling with a float consumption rate	7	35	49
After leveling without a float consumption rate	2	25	64

The sum of the absolute deviations between daily resource usage and average resource usage is reduced from 69 to 25, which corresponds to an improvement of 64% (Table 1). This improvement is better than the one obtained by using float consumption rates of 90% and 50% for activities which are scheduled to start in the first and second half of the project, respectively. Even though this strategy provided a better resource utilization in terms of decreasing the fluctuations in resource usage, only two activities (i.e., Activity C and G) left with available float after resource leveling (Figure 5). At this point, a question arises to is it worth to get an extra 15% improvement (i.e., 49% vs. 64%) in resource utilization in return of losing schedule flexibility.

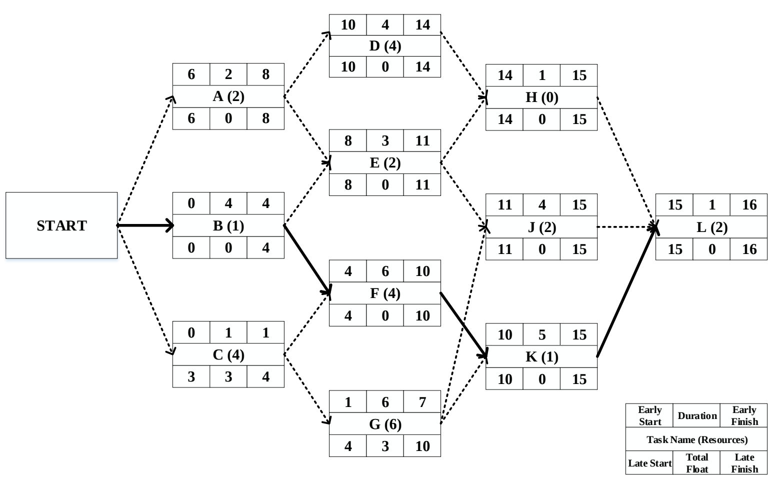

Fig. 5. Network after resource leveling without a float consumption rate

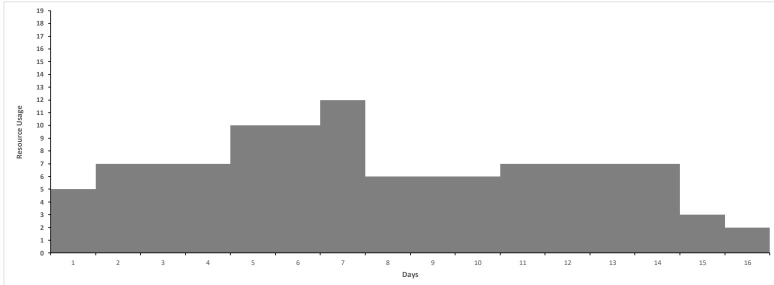

Fig. 6. Resource usage histogram after resource leveling without a float consumption rate

4. Conclusion

The use of all available float of activities in a project can easily result in failure to achieve project goals. The literature review revealed that studies exist focusing on resource leveling models considering the float loss cost. Nevertheless, the use of a float consumption rate instead of float loss cost has not been considered in these studies. To fill this gap, an excel-based resource leveling model that allows a scheduler to assign float consumption rates to each activity according to a preferred criterion. Thus, a scheduler can achieve a balance in resource utilization and schedule flexibility. The proposed model has two modules, namely, (1) scheduling module, and (2) resource levelling module. A scheduler does not need an extra scheduling software because the scheduling and the resource leveling are handled by an Excel-based approach. The model is demonstrated on an illustrative example. Indeed, it was observed that the model provided a smoother resource histogram while maintaining the schedule flexibility. On the other hand, the proposed model has limitations too in that it considers only one objective function, it cannot handle multiresource leveling, and it does not consider the point-to-point relations which are claimed to be better from traditional precedence relationships of CPM. Developing a model that considers different objective functions and multiple resources would be a potential improvement for this study.

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Resource-constrained scheduling in repetitive projects

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Abstract

The optimal allocation of resources is a critical factor for the successful implementation of construction projects since it ensures stability in the work execution. Resource allocation is a complex optimization analysis, especially when it comes to linear or repetitive projects. In such projects, the Line of Balance scheduling method is preferred to the CPM-based scheduling. This study aims at developing a multi-objective model for optimizing resource allocation in such type of projects under different objective criteria and problem constraints. The practical implications of each criterion in terms of project cost are considered to provide some guidance on what criterion may be more suitable under particular circumstances. The optimization is obtained through a genetic algorithm formulation implemented in a spreadsheet form and with the use of a commercial optimization software. Indicative evaluation results are presented on the basis of a case study and show that criteria involving as decision parameters the cumulative exceedance of resources above a given resource availability threshold or the total number of resource movements in and out of the project may be the most appropriate to simulate actual costs and provide effective resource allocation solutions.

Keywords: resources allocation; resource leveling; optimization; genetic algorithms; line of balance method; repetitive projects.

1. Introduction

The problems of resource-constrained scheduling and optimal resource allocation are of crucial importance in project planning and implementation as well as in cost control. The challenge in optimizing resource usage and project duration emerges from the fact these parameters inversely affect each other. In particular, if a reduced project duration is sought, the resource requirements are increased and resource leveling becomes more challenging adversely affecting the project cost and vice versa. Therefore, certain combinations of the input parameter values which lead to a suitable balance between the two objectives are sought. Optimal resource allocation refers to both restricting the resource requirement within the availability limit and smoothing resource usage throughout project execution to enhance stability and quality of the construction process.

In case of linear or repetitive projects (e.g., high-rise buildings, complexes of identical residences, tunnels or pipelines), the difficulty of optimization is remarkably increased. A basic technique for scheduling linear projects is the Line of Balance (LOB) method which can further assist in performing the time-resource optimization. The LOB technique, originally designed by the Goodyear Company in the early 1940s and further developed by the U.S. Navy in the 1950s, has been used as a planning and scheduling technique in the construction sector since the early 1970s. Carr and Meyer (1974) presented the LOB technique in its present form [1]. In the following years, attempts were made that resulted in revised and extended scheduling models and tools based on this method [2-7].

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Resource allocation and management in construction has been extensively studied in the past and several works have been reported in the literature. The majority of them have been developed based on the CPM scheduling technique (indicative works can be found in [8-13]). In contrast, there are fewer efforts structured on the LOB method and, among them, are those found in [14, 15]. Existing works present two types of limitations. First, they mainly focus on resource leveling and not as much to the general multi-objective, multi-constraint resource management problem. Next, the decision parameters are somewhat theoretical and not entirely representing more practical effects. For instance, the main parameter for resource leveling is traditionally some type of statistical moment of the obtained resource histogram. Although such a parameter is mathematically sound for a theoretical analysis, there is no direct explanation of the effect that a non-uniform resource diagram has on the project cost. To account for such discrepancies between theoretical and practical considerations of the decision parameter(s) and to obtain a more complete view of the effectiveness of different decision criteria, the present study analyzes and evaluates alternative optimization structures and criteria based on practical implications of those structures and criteria.

2. Proposed Model

Resource allocation problems are associated with two main parameters, the number of resources used day by day and the project duration, and aim at finding a balance between them. Exceeding the project time limit typically incurs additional cost in the form of a penalty or as a result of the project not being operational for some planned period. Additional cost may also take place if the project asks for more resources than available at any time period during the project execution. Further, another cost component is present if the resource diagram is not levelled with this cost to represent the expenditures for bringing in and letting out (or keeping idle) resources during the project execution. In fact, resource levelling usually softens the resource overallocation problem (except if very strict resource availability exists) since there are no large resource peaks that extensively exceed the constraint.

In this work, a number of modelling techniques to improve the resource graph of a repetitive type of project, based on time and resource availability constraints, are presented and compared. The main parameters and the mathematical relationships that govern the scheduling of repetitive projects are the following. If C is the number of crews used in an activity and t is the activity duration in one unit, then the production rate P is calculated as:

$$P = \frac{C}{t} \tag{1}$$

Further, the start time of the activity at the n-th unit, t_n, is given by the equation:

$$t_n = t_1 + \frac{1}{P} * (Q_n - 1) \tag{2}$$

where t_1 is the start time of the first unit and Q_n is the number of units that have already been produced; the finish activity time in the n-th unit is calculated by adding the activity duration t to the start time of the same unit.

In order to smooth out the project resource diagram, the optimization model considers two types of (independent) variables, the number of crews in each activity and the time lags between activities. Controlling such variables allows to adjust to any desirable resource level and to avoid activity accumulation at certain time frames. The problem, however, has two conflicting objectives, resource confinement/levelling and project duration restriction. The second parameter is taken into account in this study as a model constraint. Other constraints include the number of available crews and the maximum time lag permitted between consecutive activities in order to keep the number of feasible solutions manageable.

Individual objectives of the optimization structure are the following:

- Minimization of the maximum resource peak (maxR) for a specific project completion deadline. This process can be thought as a "piston" that presses the resource peaks down towards a finally levelled diagram.
- Minimization of the cumulative resource excess above the resource availability level (ExcessBaseR). The optimization parameter in this case is the sum of the resource surplus over the resource availability threshold in time. This criterion may be associated with the fact that extra resource may be engaged at a higher than the usual resource unit cost (e.g., overtime work). To avoid isolated extreme resource peaks, the daily resource exceedance values may be considered with some exponential form.

- Minimization of the standard deviation of the daily resource values (StDevR). This is a common criterion used for resource levelling. In fact, from the mathematical point of view, such a criterion macroscopically develops a quite levelled resource diagram, in practical terms however, it cannot avoid the continuous fluctuations of the diagram values from day to day, a situation that is not desirable in projects.

- Minimization of the resource movements in and out of the project in time (SumΔR or CountΔR). This criterion aims to minimize the resource movements avoiding or reducing the corresponding cost (both economic and "social" – the morale of workers from an unsteady working status). Depending on how the cost develops, either the sum of the resource movements or the number of times that a movement (of one or more resources) is needed (or both) can be considered as the optimization parameter.

The above parameters have been included in a multi-objective objective function of the following form:

$$min\ F = w_1 * max_R + w_2 * Excess_{BaseR} + w_3 * StDev_R + w_4 * Sum\Delta R + w_5 * Count\Delta R + w_6 * D \quad (3)$$

where w_1, …, w_6 are weights for the individual parameters associated with the cost resulting from any particular "deficiency" of the resource allocation diagram. The project duration D has also been included in (6) as a decision parameter and can be considered, in combination with any other resource-related parameter, as a secondary objective (i.e., with relatively low weight value) to obtain the lowest possible duration after optimizing the primary objective.

Based on the above analysis and depending on the parameters of a specific scheduling solution, the number of resources per activity can be calculated at every time period leading to the cumulative (for all activities) project resource diagram. This process has been implemented in an Ms-Excel spreadsheet and the resource graph is automatically produced with all quantitative characteristics that describe the effectiveness of the solution in accomplishing the optimization objectives. Figure 1 shows the graphical results obtained automatically by the software for a specific solution; (a) the LOB diagram of the solution; (b) the individual resource allocation for each project activity (corresponding to the LOB diagram); and (c) the cumulative project resource allocation diagram. The optimization is performed through genetic algorithms (GAs) via a commercial optimization software (Palisade Evolver 7.5) which works as an Excel add-in.

3. Case study

A case study example illustrates the project scheduling and resource allocation under different optimization criteria for a construction project referring to a complex of 20 similar residences (150m2 each). The project input data are presented in Table 1. For each activity, the optimal crew size (based on a balanced time-cost configuration) and the required hours for the completion of one unit (residence) are inserted. The duration of a complete unit is calculated by considering an 8-hour daily working time.

Figures 1-4 present the optimization results for each of the optimization criterion described previously (a 350-day constraint for the project completion is set). In particular, Figure 1 provides a representative output for the min{maxR} criterion. The result indicates a somewhat levelled resource allocation diagram with a maximum resource value of 35. Figure 2 depicts the resource allocation diagram resulting from the cumulative daily resource exceedance above a certain limit (a threshold of 30 available resource units daily has been considered in this application). The resulting resource diagram is quite smooth with very few peaks up to the level of 35. Figure 3 indicates an optimal resource diagram following the standard deviation criterion. The general view indicates a rather smooth diagram, however, there are several and frequent ups and downs that are not desirable from a practical point of view. Figure 4 shows the resource diagram resulting from minimizing the cumulative resource movements in and out of the project throughout its execution. Rather unexpectedly, the diagram is not levelled; instead, it presents a progressive development which, however, is smoother than any other previous diagram. In case, therefore, that the main cost component is associated with the resource movements in and out of the project and there is no constraint on resource availability, such a solution may be of the lowest cost.

Table 1. Case study input data

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Activity code	Activity	Optimal crew size	Hours required for one unit	Activity code	Activity	Optimal crew size	Hours required for one unit
A	Excavation	5	120	H	Water Supply	3	100
B	Foundation	5	240	I	Electrical Installations	2	160
C	Concrete	5	520	J	Heating system & A/C	2	140
D	Masonry	6	300	K	Paintings	4	480
E	Roughcast	4	360	L	Insulation works	4	320
F	Doors & Windows	3	96	M	Landscaping	5	600
G	Floors	4	300				

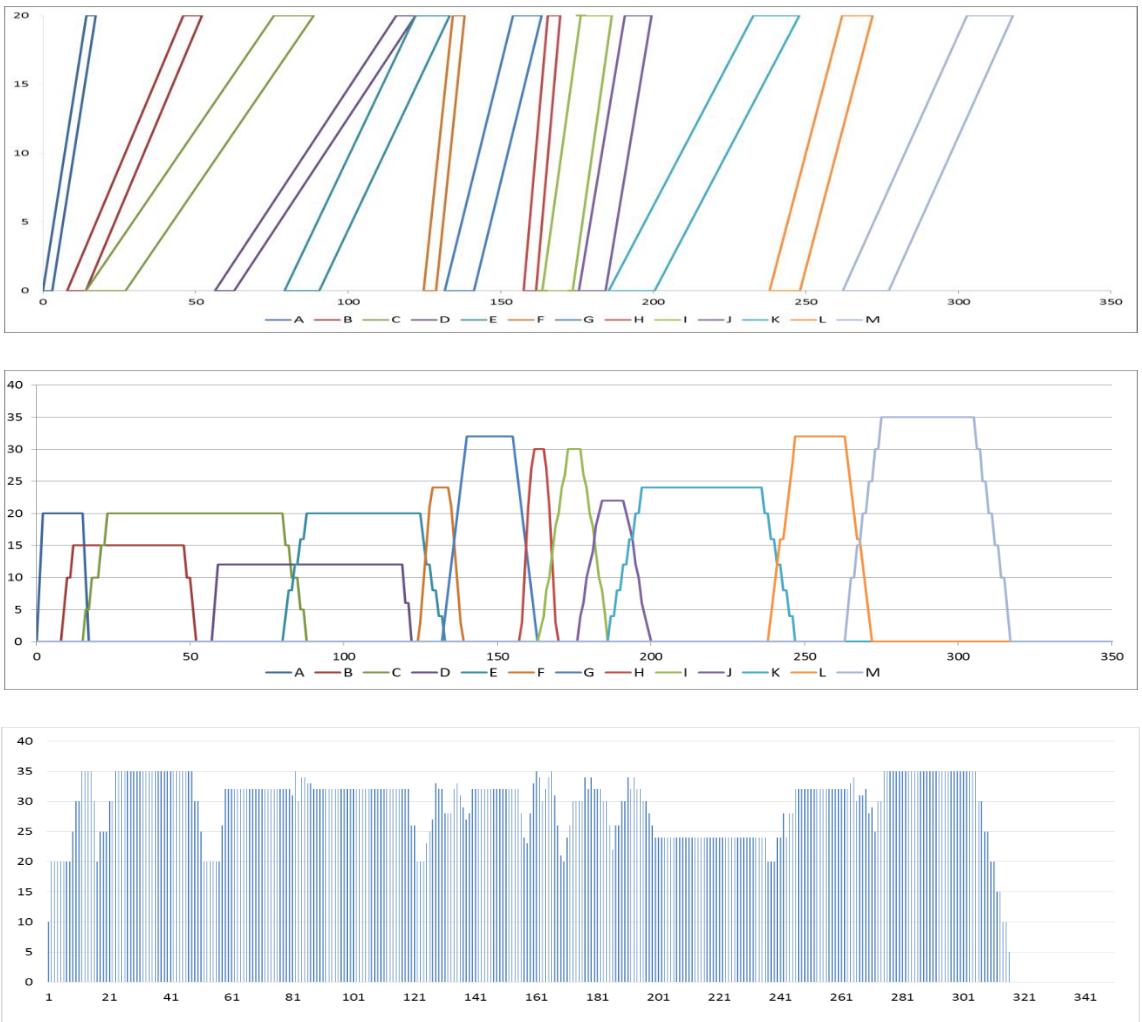

Fig. 1 Resource allocation diagram for the minimization of max R
(a) LOB diagram; (b) individual activity resource diagram; (c) whole project resource diagram

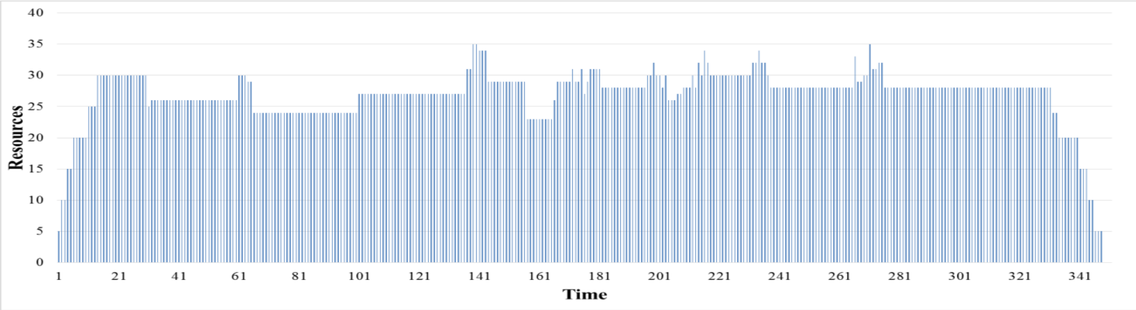

Fig. 2 Resource allocation diagram for the minimization of excess of base R

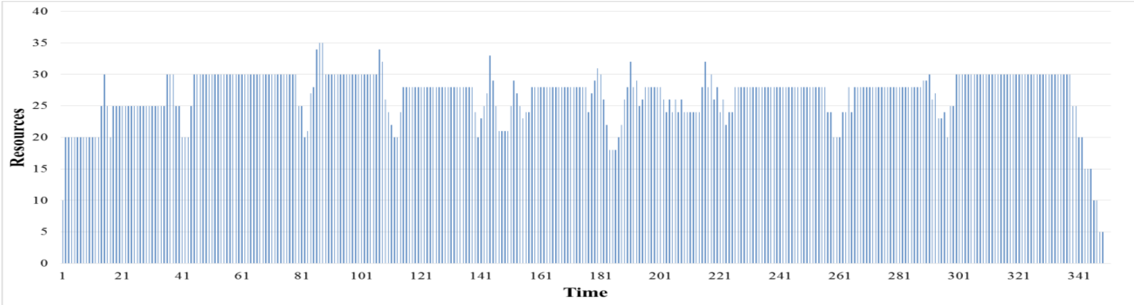

Fig. 3 Resource allocation diagram for the minimization of the standard deviation

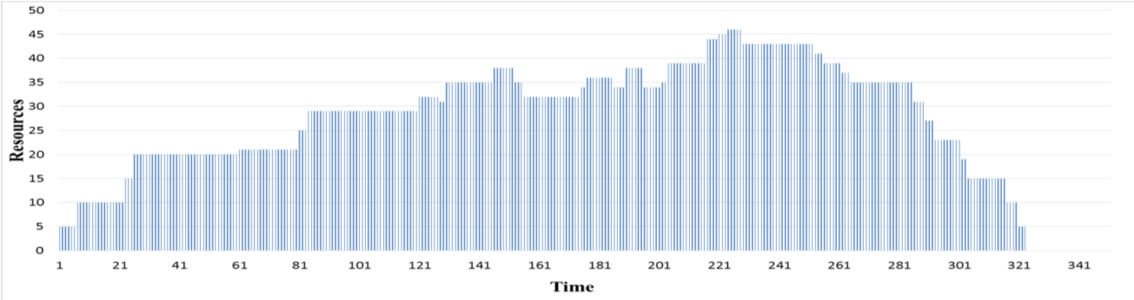

Fig. 4 Resource allocation diagram for the minimization of the cumulative resource movements

Although differences are not extreme, the experimentation with the current and other case studies provide some indications that the cumulative excess of the resource limit criterion may be the most appropriate for resource levelling in practical applications while the cumulative resource movement criterion may be primarily used if the corresponding cost is prevailing. Combination of these two (or any other) criteria, based on weight balancing, can provide intermediate solutions forming Pareto curves between optimization parameters.

4. Conclusions

The resource allocation problem is a difficult combinatorial problem which aims to develop an optimal balance between the resource usage and the time required for project completion. Scheduling projects of linear or repetitive structure based on the CPM technique is challenging and, for that reason, the employment of the Line of Balance method has prevailed in such cases. In this work, a multi-objective model for optimizing resource allocation under different objective criteria and problem constraints is presented. The practical implications of each criterion in terms of project cost are considered to provide some guidance on what criterion may be more suitable under particular circumstances. Five such criteria are comparatively evaluated, namely the minmaxR_i criterion (R_i indicates the daily resource requirements of a particular scheduling solution throughout the project execution), the cumulative excess of the resources required daily in comparison to the resource availability during the project execution, the standard deviation of the resource histogram, and the total number of resource movements in and out of the project all over its duration in two distinct forms, the sum of resource moved or the number of times that some resource movement takes place.

The model has been implemented in a spreadsheet environment with all inputs, calculations, and outputs to be handled by the software while the optimization is obtained through a genetic algorithm and employing a commercial optimization software that comes as an add-in to the spreadsheet software. Results from a case study presented in the present work and further experimentation indicate that, although there are no extreme deviations in the results, objective criteria involving as decision parameters the cumulative exceedance of resources above a given resource availability threshold or the total number of resource movements in and out of the project may be the most appropriate to simulate actual costs and provide effective resource allocation solutions.

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A Conceptual Framework for Sustainable Road Infrastructure Project Implementation in Developing Countries

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Abstract

Evidently, no generally accepted framework, concept and constructs currently exist although notably a lot of research has been made in the arena of Sustainable Road Infrastructure Project (SRIP) implementation. As a matter of fact, there are differing views by scholars regarding the SRIP implementation theory thereby making it a hazy and vague concept which is still a subject of debate. Till date, there has been a varied understanding of sustainability in terms of infrastructure development. This paper introduces a conceptual framework integrating the existing frameworks while considering the gaps in the literature and suggesting other criteria to succintly help in addressing those gaps.
The methodological approach adopted for the study was acontent analysis of published peer-reviewed journal articles discussing Sustainable Infrastructure Development. The conceptual framework herein introduced, defines the criteria and indicators to be considered in the implementation of SRIPs in developing countries. It subsequently shows the various constructs that influence successful implementation of SRIP in developing countries. The framework developed in this paper can be generally applied in the implementation of SRIPs in developing countries.

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Keywords: Conceptual Framework; Developing Countries; Sustainability; Sustainable Development; Road Infrastructure.

1. Introduction

According to the World Bank [28], although developed nations comprise 17% of the entire world's populace, they are responsible for the release of 66% of the world's GHG (Green House Gas) pollutants into the atmosphere. However, it is developing nations that will be significantly affected by the consequent effects of extreme weather conditions. These signals question developing countries' obligation to Sustainable Development (SD). As a result, in questioning the readiness of the various industries, it has been established world-wide that, the transportation industry contributes to about 25% of CO_2 (Carbon dioxide) contaminants, while as a subset of this industry, road transport contributes 80% of such contaminants [29].

In light of the identified concerns and the new agenda for SD, the infrastructure development sector and every aspect of society has been burdened with a critical role to play to attain a sustainable society [14]. Thus, it becomes evident that, within the area of infrastructure development projects, irrespective of their size, design, build, operation,

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maintenance, and deconstruction, consideration would have to be given to sustainability throughout their entire life-cycles. It is expected that policies such as sustainable procurement, sustainable monitoring, and sustainability reporting using appropriate requirements, become gradually become pertinent specifications required by clients and key stakeholders for the specific sectors to win work or remain competitive [23]. Reliable and sound road transport system is the core of sustainable economic growth, which contributes to poverty alleviation, distributed prosperity and improved quality of life in developing nations [22]. A significant part of the Sustainable Development Goals (SDGs) focuses directly and indirectly on Sustainable Infrastructure Development (SID). One of the objectives of the SDGs is that,, all nations should provide access to sound, affordable, accessible and sustainable transportation systems, such as infrastructure for all, enhancing road safety, particularly by expanding public transport, with special consideration to the needs of those in insecure situations such as women, children, individuals with disabilities and older people by the year 2030. Thus, the road infrastructure industry cannot be left out of the sustainability agenda since it forms a significant part of infrastructure development. Stakeholders in the road infrastructure sector are under immense pressure to look for economically feasible, socially viable and ecologically responsible project outcomes or procedures that will bring about Sustainable Road Infrastructure Development (SRID). This will demand not only the incorporation of sustainability guidelines throughout projects' life cycles, but also, the assessment of outcomes and the consideration of responsibility during project delivery. Even though in an ideal sense, the principles of sustainability should fuel road infrastructure development, many stakeholders are involved in the process and this seems to complicate the matter. With any given road infrastructure development project, stakeholders have their own concerns, main priorities, and interests, leading to differing targets in the project delivery. The professionals similarly face the challenge of accepting and deciphering strategic sustainability goals into real action at project-specific levels [26]. This is further hindered by the varied vested interests of project stakeholders and the multi-dimensional viewpoints of sustainability, coupled with the absence of a carefully planned decision-making method and compiling information at various categorized levels in road infrastructure project development.

Decision-making for SRID, therefore, requires the use of new techniques that are able to incorporate and synthesize all the perspectives and differing points of opinion, in an all-inclusive way [9, 19]. This procedure necessitates the application of a well-practicalized structure and an evaluation strategy, that is able to guide stakeholders through the decision-making methods for SRID. Regrettably, at this instance, such a structure for planning the information needed in decision-making is not yet available, or at least has not been decided upon by the different professions and areas of actions in the road infrastructure sector in developing countries. The lack of an agreed structure that will assist stakeholders to achieve greater sustainability in RID is a major concern [2].

Literature in the field indicates the existence of initiatives endeavoring to develop infrastructure sustainability assessment indicators and tools [5, 26, 27, 20, 8, 4, 12, 21], but they do not center on a specific type of infrastructure such as roads. Although there are existing Sustainable Roads Assessment Tools such as one developed by Australia's Victorian State Road Agency (VicRoads) in 2007, GREENROADS, Envision, among others, the adoption of these tools is rather limited and unclear.

Whilst focusing on assessing the end results, the assessment tools did not probe into identifying and addressing precise issues that influence the gap between sustainability efforts and their real deliverables during project delivery – which are the crux of every sustainability initiative. This is also coupled with the fact that these tools are many, with varied criteria and indicators.

2. Sustainable Road Infrastructure Development (SRID) Concept

Though studies have been undertaken in the discipline of SRID implementation, no generally accepted SRID concept and constructs currently exist. As a matter of fact, scholars have diverse thoughts about the SRID theory making the concept a continuing subject of debate as well as, still a hazy and ambiguous concept [3, 11]. So far, different persons have a diverse understanding of sustainability in terms of infrastructure development [3, 24].

Sustainable Infrastructure Development is also a cross-cutting matter and connotes diverse things to different individuals. The analysis of associated research shows several meanings are available [15, 30, 10, 17] and there is a discrepancy with respect to scope and perspective. In simple terms though, Sustainable Infrastructure Development is best defined as the subdivision of sustainable development and its application to infrastructure development. According to CRISP [7], infrastructure development involves all planning, designing, developing, producing, modifying or maintaining of the built environment and comprises producers and dealers of materials, clienteles, contractors, consultants and users of the final product. Therefore, Sustainable Infrastructure Development can be defined as a subsection of sustainable development, which encompasses issues such as procurement, project planning and organization, material selection, reusing, and waste reduction.

In several literatures, a common description of Sustainable Infrastructure Development, is defining it as 'the construction and responsible management of a healthy built environment grounded on judicious use of resources and environmental values [15] and a myriad of additional descriptions focused on the ecological part of sustainability. Ceres [6] defines Sustainable Infrastructure Development as the design, construction, and usage of the end product in a way that balances the social, economic and environmental practices needed to sustain human justice, diversity, and the functionality of natural systems. The American Society of Civil Engineers (ASCE) also describes Sustainable infrastructure as a structure that offers ecological, economic and social welfare, presently and for the future. According to the United States Environmental Protection Agency (USEPA), Sustainable Infrastructure consists of a collection of products, tools, and practices that use natural processes to improve general ecological quality and offer functional services. Sustainable infrastructure considers strategies, approaches, and investments that reliably offer active schemes over a long-term with sufficient usage, repairs and replacement (USEPA). A few of the current descriptions are all-inclusive and cover the entirety of the idea. Therefore, the SID concept covers a wider scope and considers different dimensions. In this study, Sustainable Road Infrastructure Development could, therefore, be defined as follows: Designing, building, operating, maintaining and deconstructing road infrastructure members in a way that balances the societal, economic and environmental concerns necessary to sustain human justice, diversity, and the functionality of natural environment.

Various authors have divergent views on the concept of SID and its basic elements or variables. Lim [18] agreed that although sustainability is applicable in the infrastructure sector, there is a lack of agreement on the implementation process and lack of understanding of the criteria and indicators as well. Conversely, it should be noted that a number of studies have been undertaken in the field of SID. The literature review conducted revealed that there has been extensive research [1, 22, 16, 18, 5, 26, 27, 8, 12] on sustainability features (constructs) which have been utilized to measure SID implementation. However, there appears to be disagreement among the various identified features by individual researchers and institutions.

3. Research Methodology

The research was conducted with reference to existing theoretical literature as well as published and unpublished literature, with a deep exploration of their context in order to meetthe research objectives. The study is mainly a literature review and seeks to develop a conceptual framework for successful implementation of SRIP in developing countries. This is presented through the discussion of the concept of sustainable road infrastructure development.

4.Criteria and Indicators of Sustainable Road Infrastructure Project Implementation in Developing Countries

In a quest to determine the sustainability criteria and indicators for road infrastructure project implementation in developing countries, a review of existing sustainability rating tools and schemes that are applicable to infrastructure development was conducted. The literature review carried out did not seek to develop or argue the validity of specific sustainability criteria and indicators. Rather, it sought to identify and compile the relevant criteria and indicators in order to create a general list of infrastructure sustainability features for road infrastructure project implementation. The review focused on sustainability models, frameworks and guidelines for general infrastructure projects developed by individual researchers, institutions and professional bodies. The criteria and indicators for frameworks and models such as CEEQUAL, FIDIC's Project Sustainability Management (PSM) Guidelines, BE[2]ST-In-Highways, Envision^{TM}, Green Guide for Roads, GreenLITES, GreenPave, Greenroads, I – LAST, and INVEST were thoroughly reviewed. CEEQUAL was the most comprehensive framework which considered eleven (11) criteria namely, Project Management; Land Use; Landscape; Ecology & Biodiversity; The Historic Environment; Energy and Carbon; Material Use; Waste Management; Transport; Effects on Neighbours; Relations with the Local Community and other Stakeholders.

Besides the various sustainability models, frameworks and guidelines for infrastructure projects developed by institutions and professional bodies, there is a fair number of research works that attempted to develop sustainability frameworks and sustainable criteria and indicators for infrastructure projects. A comprehensive literature review was done on six main studies, as evidenced in Montgomery, Schirmer and Hirsch [22], Lim [18], Transport for New South Wales [25], Assah Amiril et al [1], Ugwu & Haupt [26], and Huang & Yeh [13]. Lim [18] and Ugwu & Haupt [26] are the most comprehensive studies which considered most of the criteria and indicators in the other studies and frameworks.

Lim [18] in his study identified twenty-three (23) critical sustainability factors specific for Australian road infrastructure projects. These are air quality, water quality, noise and vibration, erosion and sediment control, flora and fauna, environmental and social impact assessment, life cycle cost, project risk, cultural heritage, inter-modality of transport, functional performance of physical asset, community involvement and public governance, liaison with client, liaison and collaboration with internal stakeholders, type of contract and project governance, compliance with contract and project specifications, hazardous goods, road user safety, road worker safety, quality control, supply chain management, waste management and recycling. These 23 critical sustainability factors are clustered into ten (10) categories; environmental, economic, social, engineering, community engagement, relationship management, project management, institutional sustainability, health and safety, resource utilization and management.

A study by Montgomery et al. [22] in their research sought to develop a sustainability rating system for road infrastructure in developing nations. The study provided a broad set of environmentally sustainable road features. The authors grouped the sustainability features into 5 groupings; quality of life, Project leadership, Natural world, Natural resource management and resilience, and greenhouse gas emissions. Existing literature also reveals that different frameworks have adopted similar criteria for sustainability under different titles. Hence, for a successful implementation of SRIP, it is imperative that stakeholders integrate and build consensus on the appropriate features and understand its implementation.

In a research that identified Key Performance Indicators (KPI) for infrastructure in the South African construction industry, Ugwu and Haupt [26] developed a comprehensive list of key sustainability items and their indicators. These constructs incorporate internationally accepted sustainability metrics such as the economy, environment, and society. Furthermore, as suggested by the industry, they incorporated other performance-based indicators such as health and safety, resource utilization and aspects related to project management.

From the conceptualized sustainability models and frameworks discussed above, CEEQUAL as well as a matrix of criteria and indicators established by Ugwu & Haupt [26], and Lim [18] are the most comprehensive conceptual frameworks of sustainability criteria for infrastructure development. The selection of the variables for this study is anchored around these three (3) frameworks. Almost all the frameworks and models studied have some common constructs conceptualized on a frequent basis. Using the reviewed conceptual frameworks as examples, it became clear that the cost of the models were based on the three dimensions of sustainable development (Economy, Society, and Environment). The various sustainability criteria and indicators (constructs) are contained within the following main domains: Social and Cultural Sustainability; Economic Sustainability; Environmental Sustainability; Institutional Sustainability; Health & Safety; Project Management; Resource Utilization and Management; and Engineering Performance. However, the current study brings into focus public participation; climate change response; and stakeholder management. These three additional constructs were not found in the identified models and frameworks. The gaps identified in the literature review were these three additions and were found to be peculiar to developing countries. Thus, the SRIP implementation conceptual framework in this study consists of eleven (11) features.

Table 1: Sustainable Infrastructure Development framework comparison

No.	Framework	Features
1.	Proposed Framework for this study	Social and Cultural Sustainability; Economic Sustainability; Environmental Sustainability; Institutional Sustainability; Health & Safety; Project Management; Resource utilization and Management; Engineering Performance; Climate Change Response; Public participation; and Stakeholder management.
2.	CEEQUAL – Civil Engineering and Environmental Quality Assessment and Award Scheme	Project Management; Land Use; Landscape; Ecology & Biodiversity; The Historic Environment; Energy and Carbon; Material Use; Waste Management; Transport; Effects on Neighbours; Relations with the Local Community and other Stakeholders.
3.	FIDIC's Project Sustainability Management (PSM) Guidelines	Equity; Health; Human rights; Education; Housing; Security; Population; Culture; Integrity; Atmosphere; Land; Oceans, Seas & Coast; Fresh Water; Biodiversity; Economic Structure; Consumption & Product Patterns; Institutional Framework.
4.	BE^2ST-In-Highways	Social Carbon saving; Life Cycle Cost; Traffic Noise; Hazardous waste; Water Consumption; waste reduction (including in-situ materials); waste reduction (including ex-situ materials); Energy Use; Greenhouse gas emissions.
5.	Envision^{TM}	Climate; Natural World; Resource Allocation; Leadership; Quality of Life.
6.	Green Guide for Roads	Mobility for All; Transportation Planning; Environmental Impact; Energy and Atmosphere; Materials and Resources; Community Impact; Innovation and Design.
7.	GreenLITES	Innovation/Unlisted; Materials and Resources; Energy and Atmosphere; Water Quality; Sustainable Sites.
8.	GreenPave	Pavement Technologies; Energy and Atmosphere; Materials and Resources; Innovation and Design.
9.	Greenroads	Pavement Technologies; Materials and Resources; Energy and Atmosphere; Construction Activities; Access and Equity; Environment and Water,
10.	I – LAST	Materials; Lighting; Transportation; Water Quality; Environmental; Design; Planning.
11.	INVEST	Operations and Maintenance; Project Development; Systems Planning.
12.	Montgomery, Schirmer and Hirsch (2014)	Quality of life category; Project leadership; Natural world; Natural resource management; Resilience and greenhouse gas emissions.
13.	Lim (2009)	Environmental; Economic; Social, Engineering; Community engagement; Relationship management; Project management; Institutional sustainability; Health and safety; Resource utilization and management.
14.	Transport for New South Wales (2012)	Environmental category (GHG emissions, water, pollution control, noise management, resource management, waste management, material consumption and biodiversity); Social category; (stakeholders' relationship, communities/public acceptance and heritage conservation); Economic category (corporate sustainability).
15.	Assah Amiril et al (2014)	Environment; Economic; Social; Engineering/resource utilization; Project administration.
16.	Ugwu & Haupt (2007)	Economy; Environment; Society; Resource Utilization; Health and Safety; Project Management/Administration.
17.	Huang & Yeh (2008)	Ecology; Landscaping; Material; Waste Reduction; Water Conservation; Energy Conservation.

Table 2: Conceptual Framework Features

No.	Features (Criteria)
1.	Socio-cultural sustainability (SCS)
2.	Economic Sustainability (ES)
3.	Environmental Sustainability (EnS)
4.	Institutional Sustainability (IS)
5.	Health and Safety HS)
6.	Project Management (PM)
7.	Resource Utilization and management (RUM)
8.	Engineering Performance (EP)
9.	Climate Change Response (CCR)
10.	Public Participation (PP)
11.	Stakeholder Management (SM)

3.1. Structural Component of the Framework

The integrated SRIP implementation conceptual framework for developing countries, is derived from Social & Cultural Sustainability (SCS); Environmental Sustainability (EnS); Economic Sustainability (ES); Institutional Sustainability (IS); Health and Safety (HS); Project Management (PM); Resource Utilisation and Management (RUM); Engineering Performance (EP); Climate Change Response (CCR); Public Participation (PP); and Stakeholder Management (SM). The SRIP implementation conceptual framework is not based on prior study or examination and is composed of SCS, EnS, ES, IS, HS, PM, RUM, EP, CCR, PP, and SM. It is a multi-dimensional structure.

The theoretical underpinning relating to this is derived from the works of Lim, [18]; CEEQUAL, [5]; and Ugwu and Haupt [26] as discussed earlier on. The conceptualized framework is the notion that implementation of SRIPs is related to the evaluation of a number of variables, such as SCS, EnS, ES, IS, HS, PM, RUM, EP, CCR, PP, and SM. It is untenable to discuss the principal variables without reference to variables of climate change response, public participation and stakeholder management and the inclusion of the other variables. The evaluation will depend on the implementation and assessment of several indicator variables under each of the variables.

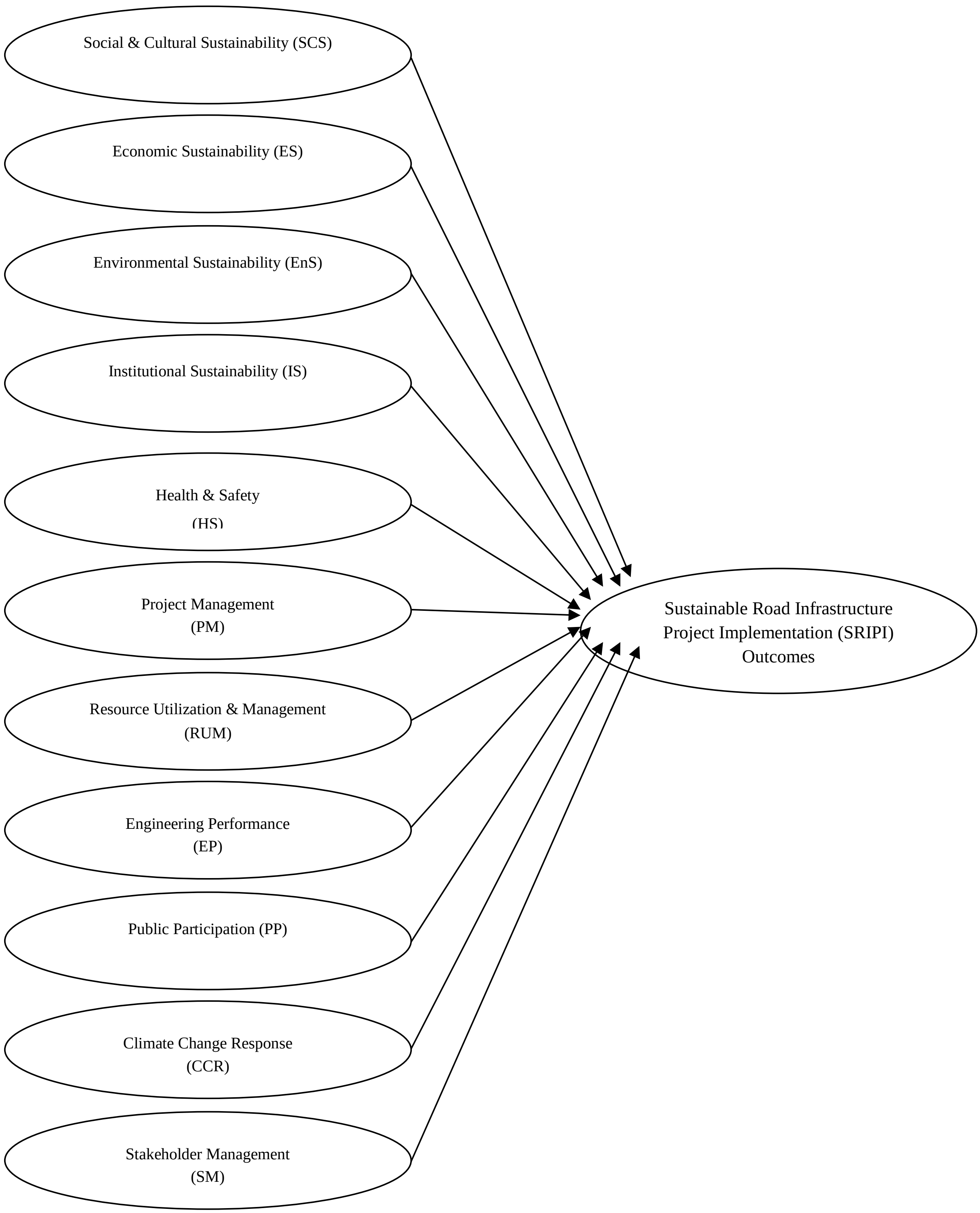

Fig. 1: Integrated SRIP Implementation Conceptualized Framework

5. Conclusion

This paper proposes a conceptual framework for the implementation of sustainable road infrastructure projects in developing countries. After a thorough analysis of earlier studies, it has been established that various sustainability pundits in the infrastructure sector have differing interpretations of SRID, though some similarities can be established. It was also discovered in the literature that there are frameworks and models for assessing and rating sustainability of infrastructure projects. These frameworks and models provide insights into the application of sustainability to infrastructure projects and improve the researchers' understanding of SRID and its constructs. Nonetheless, it was obvious that there are disparities in the various sustainability frameworks and models. Moreover, the frameworks also failed to capture a number of factors affecting their implementation in developing countries.
In search of the sustainability criteria and indicators for road infrastructure project implementation in developing countries, there was the need to conduct a review of existing sustainability rating tools and schemes that are applicable to infrastructure development. The study established eight (8) sustainability criteria and indicators (constructs) from literature namely: Social and Cultural Sustainability; Economic Sustainability; Environmental Sustainability; Institutional Sustainability; Health & Safety; Project Management; Resource Utilization and Management; and Engineering Performance. However, the current study brings into focus Public Participation; Climate Change Response; and Stakeholder Management as gaps identified from the literature. These three additional constructs were not found in the identified models and frameworks. The gaps identified were found to be peculiar to developing countries. Thus, the SRIP implementation conceptual framework in this study consists of eleven (11) features.

In conclusion, the approach to sustainable road infrastructure project implementation in developing countries is still in its early stage and not fully understood in a consistent way. The findings of this study suggest that practitioners, government agencies, and academic researchers have made efforts to develop some frameworks. The proposed conceptual framework developed in this study is much more comprehensive, robust and holistically integrated for the implementation of SRIP. However, there is a need for further study to validate the developed framework.

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Alkalinity of Concrete Washout Water: A Pilot to Determine Jobsite Conditions for Potential Neutralization

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Abstract

The threat of stormwater contamination by concrete washout water from mixers, pumps, and other equipment has been identified through U.S. environmental policy for some time, primarily through the NPDES Permit Program. That said, enforcement of regulations prohibiting construction site release and spillage of this water has been sparse, at best. Recently, several urban areas and municipalities have begun levying fines upon general contractors for not taking proper measures to contain the washout water, and/or to properly dispose of it off of the construction site. This is prompting contractors, manufacturers, researchers, and other stakeholders to take notice, and to seek ways to mitigate the problem. This research continued the work of a recent project in which new containment product prototypes were developed, as part of a successful collaboration between construction management faculty and students, and their counterparts in industrial design. As the next phase of the study, this paper enumerates the findings of chemical analyses of washout water to develop a baseline level of contaminants. Primary contaminants measured include pH/alkalinity, total suspended solids, chlorides, oil and grease, and others. The authors' hope is that these findings will present a future opportunity to leverage textile, absorbents, and/or flocculants such as naturally occurring tree cellulose as potential neutralization strategies.

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Keywords: washout; environmental, concrete; alkalinity; containment

1. Introduction and Review of Literature

1.1 Regulations

The United States Clean Water Act (CWA) of 1972 established a basic structure for regulating the discharge of pollution into domestic waters [1]. As a U.S. regulatory entity, the Environmental Protection Agency (EPA) is charged with enforcing the guidelines set forth in this legislation through the National Pollution Discharge Elimination System Permit Program (NPDES). The NPDES Permit Program's Construction General Permit (CGP) affects all construction sites that disturb more than one acre of land [2]. Although the EPA instituted the NPDES permit program and its guidelines, they have passed on the authority to enforce and further regulate these practices to state-level NPDES permit programs [3]. Currently there are forty-seven states with authorized NPDES permitting programs, some of which further delegate this authority to individual municipalities through Municipal Separate Storm Sewer System (MS4) stormwater permitting [4]. State, municipal, and other entities granted this authority via the EPA are required

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to incorporate or improve upon the federal guidelines through their own, jurisdiction specific, regulations and standards. Authorized state and local entities perform inspections on GCP-regulated construction jobsites to ensure these regulations and standards are enforced.

The majority of regulations and standards found in the federal and state NPDES GCP pertain to erosion and sediment control practices required on construction jobsites [2,3,4]. Also included in this permit, however, is regulation prohibiting the discharge of wastewater produced from the washout of concrete unless managed by an appropriate control [2,3]. According to the EPA, this ban is a result of the high alkalinity levels (11-13+), turbity, and metal content found in concrete washout wastewater [5]. The dangerously high alkalinity levels are a product of dissolved limestone used in making concrete [6]. If concrete washout wastewater is not properly contained or treated on a construction site, its contaminants can reach the surface and/or ground water table by the means of storm sewers and direct disposal [5]. While contractors operating on GCP-regulated construction sites must abide by the NPDES regulations to avoid costly fines [4, 11], many contractors report that enforcement entities focus almost entirely on the erosion/sediment control [7, 11]. Although the regulations have been in effect for decades, only recently have certain entities, primarily at the MS4 level, begun levying fines related to concrete washwater discharge [7, 11]. This has led to interest in and concern by contractors, and was the impetus for this research.

The EPA and many of the state and local authorized entities provide contractors with recommended best management practices (BMPs) for use on jobsites in order to handle concrete washout waste [5]. While these BMPs represent a wide range of strategies, most all of them function such that all solid (concrete/aggregate), semi-solid (slurry), and liquid (washwater) waste produced from cleaning equipment that is used for placing and finishing concrete is to be contained and eventually treated either at an offsite facility, or by means of evaporation [2,5,7]. The design of these collection containers range from single-use bag-like containers, to more durable containers which are reusable [2,5,7]. An additional recommended BMP is the use of a subgrade pit lined with plastic which allows the contaminated wastewater to either be evaporated or removed and transported to a treatment facility off site.

1.2 Containment of Concrete Washout Waste

A pilot study conducted in 2018 by Holley, Lynn, Bush and Chavan [7] found that even with the looming threat of fines and pollution, many contractors struggle with the recommended BMPs due to the efficiency, mobility, and safety of containment products currently available (Fig. 1(a.)). This prompted those researchers to analyze the design of current containment products, and develop a new prototype container that was more practical and mobile, enabling it to realistically be implemented on a jobsite (Fig. 1(b.)). After development and testing of prototypes, they concluded that although the development of a new container had promise, the real challenge was in containing the large volume of washwater produced during the washout process [7]. “From a volumetric perspective, the water could easily make up a significant portion of the contaminated components that need to be contained, and perhaps even more difficult to do so” [7].

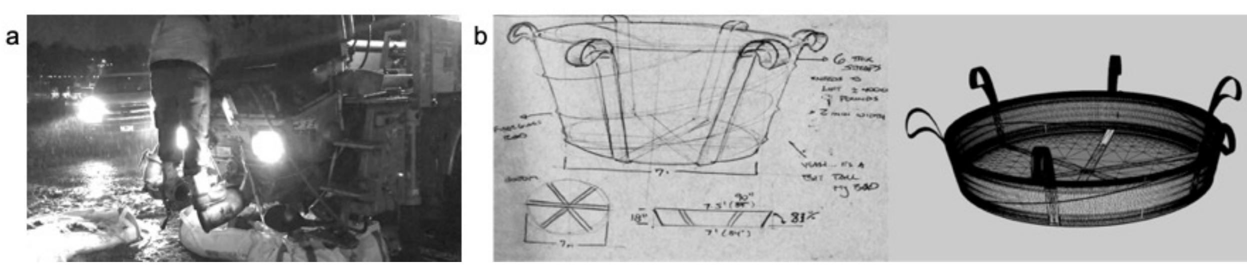

Fig.1. (a.) Vinyl Bag Being Utilized in Unsafe Conditions (b.) Protoype Developed [7]

1.3 Rationale for the Research: Determining Jobsite Conditions for Potential Neutralization

Based on the conclusions made by Holley, et al, the authors sought to continue the research by analyzing the contaminates found in the wastewater, to better understand if treating/neutralizing the washwater on the jobsite as part of the clean-up process is feasible. The specific aim of this research is to determine the chemical composition of wastewater produced in the washout process under realistic jobsite conditions, creating a baseline for which future research can use in determining a potential solution.

In order to identify and test potential means of neutralization, standards which concrete washwater should meet in order to be directly discharged on site would need to be identified. A review of relevant literature illuminated an abundance of published research pertaining to recycling concrete wastewater, but most all focused on ready mix plants and industrial concrete production sites, such as the studies by Su, Miao, and Liu, in 2002 [8], and Chini and Mbwambo in 1996 [6]. However, no significant research was found on the responsible disposal of concrete wastewater on construction sites.

This led researchers to have discussions with the EPA and State environmental management authorities in the exploration of collection standards and metrics used for evaluating contaminants found in concrete washout wastewater on a construction site. These discussions yielded there are currently no published collection standards or metrics at the federal level. Based on this, the investigators proposed the use of standards established for collecting and monitoring the discharge of wastewater produced from a permitted temporary concrete batch plant, which regulatory representatives found reasonable [4,9]. Projects requiring a large quantity of concrete have the ability to construct temporary batch plants on the jobsite under this permit, representing similar conditions to washout waste produced from mixers and pump trucks on site. Based on geographic location, the authors chose to utilize standards set at their home state level [10].

2. Methods

2.1 Variables

Due to the nature of the research, a pilot study approach was used so that future research could be better informed. Two potential options were identified for the collection process; samples could either be collected from a construction site in actual conditions, or from a simulated scenario in a lab. Although collecting or developing samples in a lab environment would provide researchers with control of more variables, the authors decided that sample collection from working construction sites would give this research the advantage of identifying how actual jobsite conditions affect the data collected. That said, realistic site conditions provide a range of variables that could affect the composition of samples. Variables identified for which researchers had reasonable control included the type of equipment being cleaned, compressive strength of concrete (i.e., cement content), amount of water used in the clean-up process, and the size/type of waste container. More difficult to control, but identifiable, were agitation and extraction practices, source of the water used in clean-up, and the presence of admixtures such as plasticizers, calcium, and fly ash.

Discussions with industry professionals suggested that the cleaning of concrete pump trucks produces the largest amount of contaminated washout waste on a typical jobsite, as compared to that produced by a mixing truck's direct chute. During the cleaning process of a pump truck, its hopper contains an average of ¼ CY to ½ CY of solid waste in the form of uncured concrete. After solid waste is discharged from the hopper, between 40 and 50 gallons of water is typically used to clean the residual concrete from the interior of the hopper and the boom pipe [7, 11].

Samples from three residential concrete pours were collected. The pour identification, compressive strength, admixtures, and water source used for cleaning is displayed in table 1.

Table 1. Pilot Study Pour Makeup

Pour ID	Compressi ve Strength	Admixtures	Water Source
A	3000 psi	1% calcium chloride, fly ash	Well
B	3000 psi	N/A	Municipal Utility
C	3000 psi	N/A	Municipal Utility

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2.2 Collection

For each pour, the pump truck emptied the remaining solid concrete/aggregate left in the hopper into a 16 CF portable washout box (Fig. 2(a)) supplied by the authors. The operator then cleaned the residual concrete remaining in the hopper with a water hose, to which a flow meter was attached and used to quantify the amount of water that was being used to clean the truck. To determine the effects of water quantity and potential dilution, samples were taken at three separate intervals based on the amount of water used to clean the pump truck: 10 gallons, 20 gallons, and 40 gallons (Fig. 2(b)). At each stage, researchers collected sample sets from the portable washout box in triplicate, to identify any abnormal data and to ensure the samples taken were an accurate representation of the chemical composition of the wastewater at that point in the washout process.

Fig. 2. (a) Portable Washout Box and (b) Sample Collection

2.3 Analysis Protocol

Sample sets were labeled based upon their corresponding pour ID, amount of water used as of the time the sample was collected, and the order in which each sample was taken in triplicate. Each sample set consisted of six containers which were also identified in accordance with the contents of each container and the testing requirements (e.g. the container used to test the pH was plastic, and the container used to test oil and grease was glass), based on EPA-certified lab protocol. To preserve their contents, samples were packed in ice after collection and then delivered directly to the lab, at which point the chain of custody forms were executed to begin analysis.

Testing and analysis of each sample's chemical makeup was performed by an EPA-certified laboratory. The accreditation of this lab was beneficial to this research since they routinely perform these tests and are certified to do so by the governing body that enforces these regulations, at both federal and state level.

3. Results

The analysis process underwent rigorous quality control/quality assurance parameters to ensure the sample sets were tested based on state and federal requirements by the NPDES Permit Program. Results were posted to a secure online database where researchers collated data from each individual sample set. Based on the pour mix design, location, and stage in the washout process from which the samples were collected, researchers aggregated the results for each sample set taken in triplicate (Table 2). Triplicates were averaged for analysis based on milestones signified by gallons of water used during the washout process in order identify patterns found across the data. Outlying data observed or suspected was reviewed with lab technicians to confirm results.

Table 2. Washwater Analysis Results, per regulatory standards for temporary jobsite batch plants [10]

3000 PSI μ of Triplicate Samples					
POUR 'A' February 27, 2019 Griffin, GA AdMix: 1% calcium chloride, + fly ash					
TEST	@ 10 gallons used	@ 20 gallons used	@ 40 gallons used	Units	Max per Standard [10]
pH	12.4	12.2	11.87	SU	8.5
Total Phosphorus	47.00	2.78	1.43	mg P/L	1
TSS	12,526.67	1630.00	810.00	mg/L (dry)	50
TRC	0.65	0.87	<0.02	mg/L	0.019
Chlorides	520.00	1260.00	268.00	mg/L	860
TDS	3346.67	2226.67	1009.33	mg/L (dry)	monitor
Oil and Grease	27.33	19.33	23.33	mg/L	15
POUR 'B' February 27, 2019 College Park, GA AdMix: None					
TEST	@ 10 gallons used	@ 20 gallons used	@ 40 gallons used	Units	Max per Standard [10]
pH	12.43	12.13	12.00	SU	8.5
Total Phosphorus	1.30	0.51	0.45	mg P/L	1
TSS	3030.00	1630.00	810.00	mg/L (dry)	50
TRC	0.21	1.07	0.45	mg/L	0.019
Chlorides	401.67	355.00	605.00	mg/L	860
TDS	3543.33	2610.00	8510.00	mg/L (dry)	monitor
Oil and Grease	26.00	24.67	20.00	mg/L	15
POUR 'C' March 1, 2019 Fairburn, GA AdMix: None					
TEST	@ 10 gallons used	@ 20 gallons used	@ 40 gallons used	Units	Max per Standard [10]
pH	12.67	12.63	12.30	SU	8.5
Total Phosphorus	8.35	5.87	1.64	mg P/L	1
TSS	94,933.33	36,663.33	8050.00	mg/L (dry)	50
TRC	2.19	2.19	0.90	mg/L	0.019
Chlorides	405.00	515.00	555.00	mg/L	860
TDS	4593.33	4190.00	2470.00	mg/L (dry)	monitor
Oil and Grease	22.67	12.00	16.67	mg/L	15

4. Conclusions and Recommendations

1.1 Conclusions

Data show multiple items and patterns that may be important in next steps of the research. First, that the use of more water in the cleaning process did not significantly reduce the alkalinity of the waste/washwater. Researchers believe this may be the result of water being used in the cleanout process further agitating the solid (concrete/aggregate) and semi-solid (slurry) waste in the container, causing cement in the solid and semi-solid waste to separate and further disperse in the liquid waste, continuing to contaminate the wastewater. Second, that total suspended solids (TSS) diminished substantially over the course of the clean-up process. As this is a major contaminant according to the EPA [7], data suggest that perhaps a filtration strategy could have potential. Next, some contaminants actually increased while using more water in the process, most notably the chlorides. However, data suggest that this is more prevalent when treated municipally sourced water is used, as opposed to well water. And finally, some contaminants such as total phosphorus and oil/grease are shown to be at or relatively near acceptable levels for discharge, leaving continued research to prioritize the contaminants to be neutralized.

1.2 Limitations

Researchers acknowledge that this pilot study has certain limitations. Foremost, samples collected in a quantitative sample size may more accurately represent jobsite conditions of contaminants than data from this study. While collecting samples in the field gave the authors the advantage of collecting data from realistic construction jobsite conditions, limitations on not being able to control certain variables such as the amount of solid waste remaining in the hopper or the origin of the water used to clean may have also impacted the results. Data from Pour C suggest an unusually high level of TSS, supporting this concern. From an analysis perspective, the EPA-certified lab notified researchers that due to the nature of the matrix being tested in the samples, results for Total Residual Chloride (TRC) could be inaccurate. Suspended solids found in the samples can cause the spectrometer used to test TRC to display inaccurate results. Future research may need to seek an alternative method to test for TRC.

1.3 Future Research

As this pilot study targeted the collection of concrete washout wastewater under realistic jobsite conditions, multiple opportunities can be identified for future research. A new study could include results taken from a larger quantitative sample size to more accurately represent the characteristics of wastewater samples collected during the washout process. This study could be expanded to include results from waste created by concrete having different mix designs, such as having 4000psi compressive strength, the addition of plasticizers, etc. Samples could also be collected from a simulated concrete washout scenario in a laboratory, giving researchers better control of the variables found on a construction site. The results found in this pilot study also facilitate a need to revisit the design of the concrete washout containers. Based on the results found in this study, early discussions with regulatory agencies suggest that a priority of future research should address the level of contaminants identified in the pH and Total Suspended Solids (TSS) results [4,9]. Future designs could potentially investigate fabrics, polymers or nanotechnologies such as naturally occurring tree cellulose to potentially neutralize water created during the washout process such that it could be discharged on site.

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An Overview of Real-time Occupancy Information Acquisition Method for Demand-driven Building Energy Management

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Abstract

Efficient building energy management needs to meet both energy savings and user comfort requirements, which relies on the accurate acquisition of occupancy information over time. In order to meet the data requirements of different building application environments, this paper reviews different sensor technologies based on the principle of obtaining occupancy information, and divides them into five categories, namely motion sensors, environmental sensors, radio frequency (RF) sensors, camera, and contextual sensors. A review of the fusion of multiple sensors that have been widely used for building occupancy detection in recent years has also been conducted. The pros and cons of the prior art are discussed in detail, thus future research can better fit the needs of different system control (such as heating, ventilation, and air conditioning (HVAC) and lighting systems) in different types of buildings.

Keywords: Building energy control; Occupancy information; Sensor; Fusion

1. Introduction

Building sector consumed 40% of the global energy and produced one-third of the global greenhouse gases (GHG) both in developed and developing countries, according to the United Nations Environment Programme [1]. In order to maintain a comfortable indoor light and thermal environment, the inefficient operation of HVAC and lighting systems is a considerable energy waste. Although the occupancy level can vary over time, most of the current building control systems are designed according to the regulations, which assume that all spaces in the building maintain the maximum occupancy. In this case, the lighting and HVAC systems remain work when there is no occupant in the space; and when there are few people in the thermal zone, the maximum occupancy assumption could cause unnecessary energy consumption of HVAC system and make the occupants feel cold.

Building energy management based on occupancy information has great potential for energy saving while providing a comfortable indoor environment. Only with the application of individual temperature setback periods which analyzed

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by historical office occupancy mode, the space heating and cooling loads can be reduced by 10-15％. In [2], a proof-of-concept experiment was conducted in a mock-up office, the HVAC, lighting, and plug loads were controlled considering the presence of occupancy, and the result indicated that the system was able to deliver an energy saving of 15-68％. Li, et al. [3] adopted random forest to predict personal comfort based on the collection of occupant physiological and behavioural data, and the experiment conducted both in single and multi-occupancy spaces showed that comfort was expected to increase by 80％.

Dong, et al. [4] reviewed the statistical and data mining models for occupancy and behavior modelling, such as agent-based model and k-means clustering. However, for two days of the working day, the prediction methods based on the history data can be indistinguishable. To achieve optimal demand response, real-time occupancy information acquisition is essential. In recent years, there has been a surge of interest in the application of different sensor technologies to detect the presence, count, activities of occupants and support for demand-driven building energy control. The principle of sensors acquiring occupancy information determines their placement and accuracy. Since there are different data requirements for the controlling of different subsystems in different types of buildings, it is necessary to detail review the information acquisition and processing methods for further research.

This paper aims to classify and review emerging indoor occupancy information acquisition methods to serve efficient building energy management needs. According to the type of information acquired by the sensors and its relationship with occupants, we divided them into five categories, namely motion sensors, environmental sensors, RF sensors, cameras and contextual sensors. The following chapters are arranged as follows. Section 2 defines the resolution of building occupancy. Section 3 reviews the single and multi-type sensor fusions that capture occupancy information, detailing the occupancy information acquisition path and information processing methods. And finally, in section 4, some concluding remarks and briefly discusses on limitation and future work are presented.

2. Building occupancy resolution

The resolution demand of occupancy information for different application environments varies. Melfi, et al. [5] proposed to evaluate the resolution from three aspects, which are temporal, spatial and occupancy resolution, as shown in Figure. 1. To focus on the room level, from coarse to fine, the detection of occupancy information includes identifying whether the room is occupied, occupancy count, occupants' location and their trajectory and activities during a specific time. For large-scale commercial buildings, researches are prone to divide rooms into thermal zones, focusing on occupancy differences between regions, especially to detect whether space is occupied and the number of occupants[6, 7]. In contrast, for a space occupied by a few people, such as single offices or residential building, studies pay more attention to the fine-grained information to investigate the occupancy behavior. When it comes into time dimension, the time interval of information processing is closely related to the specific application[4].

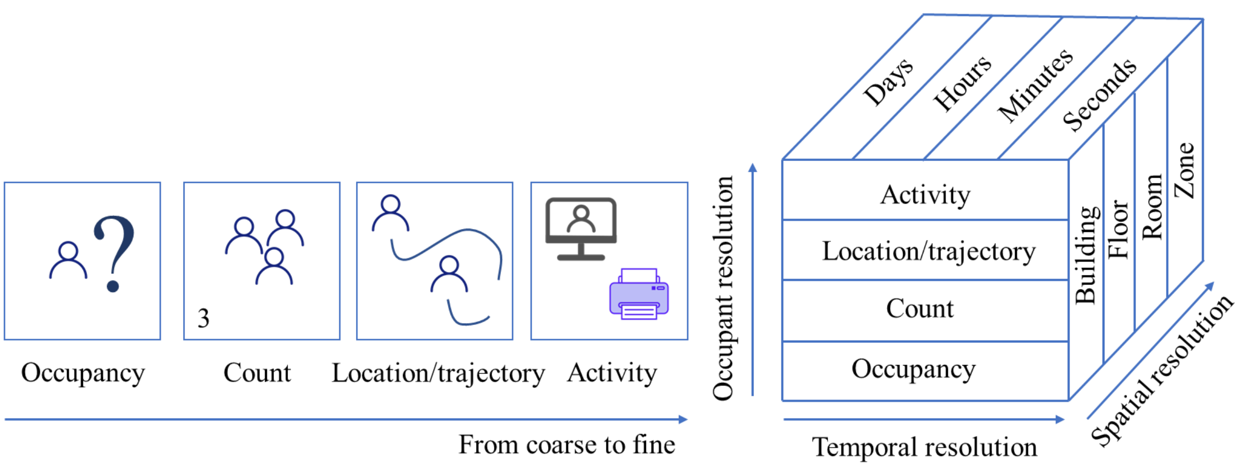

Fig.1. Spatial-temporal properties of occupancy information

3. Monitoring technologies

In this section, a comprehensive review of the most popular occupancy information acquisition sensors and their fusions is conducted. According to the principle, they are divided into five categories, which are motion sensors, environmental sensors, RF sensors, camera, and contextual sensors.

3.1. Motion sensors

The motion sensor either emits stimuli and monitors any changes reflected back or acquires a signal from the moving object itself, including passive infrared sensors (PIR), ultrasonic detectors, and radar. Among them, PIR is one of the most commonly utilized devices for occupancy detection.

In nature, all objects including humans with a temperature above absolute (-273K) produce an infrared spectrum, and the wavelength of the infrared energy emitted by objects of different temperatures is not the same. PIR sensor itself does not emit any type of radiation while works by detecting the infrared rays emitted by the human body. It detects the presence of an occupant based on changes in infrared radiation produced by the movement of him. For instance, Dodier et al. [8] constructed a belief network with PIR sensors to detect the presence of occupants in the building. The sensor network was developed and deployed with three PIR sensors, which provide occupancy detection independently, and Bayesian probability theory was applied to determine occupancy. In [9], Duarte et al. analyzed the PIR motion sensor data to identify when the occupant arrived and left the office. Descriptive statistics and two-sample t-tests (95% confidence interval) were used to summarize the long-term occupancy diversity of different rooms, and the results showed that the measured diversity factors of the occupancy data significantly differ from the guidelines recommended by ASHRAE 90.1 2004. Wahl et al. [10] proposed a distributed sensors system based on PIR to detect the moving direction of occupants and estimate the number of indoor occupants. A pair of one-way PIR sensors were deployed, and a direction-based algorithm was applied to count the number. The probabilistic distance-based algorithm was used to select the start and end of the path, compensate for PIR masking-induced deletion errors, and improve the accuracy of the occupant detection. To reduce the cost of equipment costs, Labeodan et al. [11] managed to use a PIR sensor to complete the counting task. The motion patterns were extracted from the raw sensor data with an infinite hidden Markov model (IHMM), and applied to infer the number of occupants using basic statistical regression methods.

PIR sensor-based systems are low-cost and easy to install. However, the PIR sensor with poor penetrability can only detect moving occupants which within its field of view, and occupant information is confined to presence and number.

3.2. Environmental sensors

For one thing, it is necessary to ensure the sound, light, thermal environment and air quality for indoor occupants; for another, the presence of occupants can also act on the indoor environment. Based on this idea, the environmental sensor acquires occupancy information by sensing changes of environmental variables such as temperature, humidity and CO_2 concentration.

3.2.1 CO_2 sensor

The occupant as a source of carbon emissions will affect the concentration of CO_2 in the room. For instance, Calì et al. [12] used a dynamic detection algorithm based on the mass balance equation of indoor CO_2 concentrations to estimate the presence and quantity of occupants. They assumed that the air exchange rate of the doors and windows and the CO_2 produced by each occupant are constant. To smooth out short-term fluctuations and highlight long-term trends, a moving average based on a centred rectangular window function was used to filter the CO_2 concentration. Then, in different scenarios, the PM index and OM index were introduced to evaluate the algorithm. The results showed that the simulation algorithm has better performance when providing the position information of doors and windows.

In addition to dynamic physical models, CO_2-based statistical models have also been leveraged to describe the relationship between the CO_2 concentration and occupancy level.

To avoid the truncation error in deconvolution process, Jiang et al. [13] used the FS-ELM model for indoor occupancy estimation. Locally smoothed CO_2 data was applied to eliminate the effects of data peaks and an X-tolerance accuracy was introduced to evaluate the occupancy estimation performance. Considering the nonlinear relationship between CO_2 and occupancy level, Zuraimi et al. [14] compared the performance of dynamic mass balance model with support vector machines (SVM) and artificial neural network (ANN) models. A lecture hall for up to 200 people was used for a test. The results showed that the ANN and SVM models achieve higher prediction performance when compared with the physical model.

Due to the high variability and slow response of CO_2 sensors, it is difficult to reliably correlate CO_2 levels with actual occupancy. As the occupancy rate increases, the inevitable delay in CO_2 concentration increases.

3.2.2 Multiple sensors

In addition to CO_2 sensors, other environmental sensors such as humidity, temperature, light, and pressure are also applied to provide occupancy information while monitoring the indoor environment, as shown in Table 1. Studies have shown that when CO_2 features are included, better detection performance can be obtained. However, it is worth noting that some researchers also use environmental sensors to detect occupant activities when associated with room information[15].

Table 1. Multi-environment sensor fusion system for occupancy information

Reference	Sensors	Occupancy resolution	Spatial solution	Methodology	Remarks
[16]	CO_2, humidity, temperature, light	Presence	Room	LDA, CART, RF	A proper selection of features together with an appropriate classification model have an important impact on the accuracy
[17]	CO_2, humidity, temperature, light	Presence	Room	HMM	The HMM with features through CO_2 achieves the best detection performance
[18]	CO_2, humidity, temperature, pressure	Count	Room	Wrapper based ELM	Pressure sensors are meaning for occupancy estimation
[19]	CO_2, humidity, temperature, pressure	Count	Room	Filter-wrapper based ELM	Ranges of occupants are defined
[20]	CO_2, humidity, temperature, pressure	Count	Room	HFS-ELM	Combining dynamic and static features to form a feature selection framework
[21]	CO_2, humidity, temperature	Count	Room	Wrapper based KNN and LDA	KNN performs better than LDA
[22]	CO_2, humidity, temperature, pressure	Count	Room	IHMM-MLR	The temporal dependency is captured for different instances
[23]	CO_2, humidity, temperature, pressure	Count	Room	Particle filter	
[24]	CO_2, humidity, temperature, pressure	Count	Room	LRF	Automatically learn useful features from time and frequency domains
[15]	CO_2, humidity, temperature	Activity	Room		
[25]	CO_2, humidity, temperature, and air pressure	Count	Room	CDBLSTM	

3.3. RF sensors

RF sensor-based systems include WiFi, Bluetooth, radio-frequency identification (RFID), Global Position System(GPS), ultra-wideband (UWB) and ZigBee. These systems are widely used owing to their flexible, efficient, and wide coverage, which are usually associated with location information.

3.3.1 WiFi

In recent years, with the wide availability of WiFi infrastructure in building and the ubiquitous WiFi-enabled mobile devices (MDS), leveraging routers along with MDs carried by occupants for occupancy detecting becomes feasible.

Wang and Shao [26] developed a WiFi-based Navizon indoor triangulation system for occupancy detection based on the number and location of WiFi devices in the university library. The energy waste pattern was identified through data association rule mining， and the correlation rules were evaluated by the Apriori algorithm. Considering the privacy issues, Zou et al. [27] proposed a new WiFi-based non-intrusive occupancy sensing system (WinOSS), which can provide accurate occupancy information, including occupancy presence, counting and trajectory. Routers were used to scan WiFi-enabled smartphones indoor to capture the data packets and signal strength (RSS) value. The MAC address of MDs was used as identification of occupant. Then, the Online Sequence Extreme Learning Machine (OS-ELM) algorithm was applied to infer occupancy information. To solve the possible detection error that caused by the WiFi-enabled devices not connected to the network, Wang, et al. [28] proposed a WiFi probe-based Dynamic Markov Time-Window Inference (DMTWI) model based on time series and random characteristics of the measured WiFi signal to predict the number of occupants automatically. Comparing with the traditional SVR and ARMA model, the results showed that the WiFi probe can reduce the detection fluctuation effectively.

However, require all occupants to carry a WiFi-enabled smartphone is not the case in real life. To solve this problem, Liu et al. [29] inferred the total number of people walking in a given space based only on the WiFi received signal strength (RSS) measurements between a pair of fixed transmitter/receiver antennas, and no need for occupants to carry MD. A motion model was used to simulate the effects of blocking line of sight (LOS) and scattering effects. By putting the two components together, a mathematical expression was established to represent the relationship between RSS measurements and occupancy. Finally, occupancy was inferred from the calculation of Kullback-Leibler divergence. However, RSS suffers from fluctuations greatly. Chen and Ahn [30] proposed a crowd counting system based on CSI Doppler spectrum analysis acquired by a single wireless receiver. The system used an exhaustive search feature selection strategy to reduce the number of features and improve the overall accuracy of the classification. This method can only provide a rough estimate of occupancy when the number of people is greater than 2. In [31], Zou et al. proposed a device-free occupancy detection and crowd scheme using commercial WiFi to support Internet of Things (IoT) devices. By measuring the shape similarity between adjacent time series CSI curves, an effective signal-based trend index occupancy detection scheme was developed. Finally, an information-based feature selection scheme was used to select the most representative features which are sensitive to human motion, and a crowd counting classifier based on transfer kernel learning (TKL) and information fusion was proposed to calculate the number of occupants in space.

In sum, the indirect system relies on the detection of MDs, but sometimes the occupant may not turn on the WIFI service or a single occupant may carry multiple MDs. The direct system is confined by the estimate of the number of mobile occupants while ignoring the stationary one.

3.3.2 Multi-sensor networks

The availability of WiFi and BLE sensors in smartphones makes it easy for users to carry potential positioning capabilities in their pockets, and research tends to combine the two to explore more accurate and reliable occupancy information, as shown in Table 2.

Table 2. Multi-RF sensor fusion system for occupancy information

Reference	Sensors	Occupancy resolution	Spatial resolution	Methodology	Remarks
[32]	WiFi, BLE	count	Zone	KNN	Uneven occupancy distribution leads to high energy saving potential
[33]	WiFi, BLE	count, location	Floor	DFT, Particle Filter	

3.4. Camera

Cameras for security monitoring are widely installed in public buildings, which also provide a solution for the acquisition of occupancy information. Benezeth et al. [34] proposed a vision-based algorithm to detect human presence and characterize activity with static cameras. Firstly, the objects variation was detected using the background subtraction algorithm. Secondly, the moving objects were tracked based on interest points. Finally, multiple cascades of boosted classifiers were applied for occupant identification. To alleviate privacy issues, Diraco et al. [35] presented a computational framework for occupancy detection and profiling based on pure depth data. The Gaussian average background model was applied to estimate the depth distance in crowded scenes. A semi-supervised version of the complete linkage agglomerative clustering was proposed to improve the localization in depth data. Then, the occupancy detection was implemented by means of an ensemble classification technique based on Real AdaBoost. In [36], Zou et al. proposed an occupancy detection algorithm combining the cascaded classifiers and emerging machine learning technology. The pre-classifier employed three frame difference algorithm to search for motion windows and used the HOG-SVM module to filter non-head regions quickly. Then, the main classifier utilized a convolution neural network (CNN) to classify head windows. Finally, the clustering analyzer employed K-means clustering to fuse the sequence frames to improve accuracy. If the interior layout is compact, it may cause head blockage or overlap. Petersen et al. [37] proposed an occupancy detection system based on Kinect camera installed at the room entrance. An image-based unsupervised image processing technique was proposed to determine whether a person enters or leaves a room within the camera field of view according to different moving directions of occupants.

Generally, camera-based occupancy systems have high accuracy and were commonly used to obtain ground truth. However, it still has many limitations, such as the need of large data storage, high computational complexity and interference with privacy issues.

3.5. Contextual sensors

Contextual sensors refer to entities in space such as chairs, keyboards and mice, which can be in direct contact with occupants to obtain occupant information. As shown in Table 3, a few studies that only based on chairs have made some attempts.

Table 3. Contextual sensor system for occupancy information

Reference	Sensors	Occupancy resolution	Spatial resolution	Methodology	Remarks
[11]	Chair	Count	Room	Thresholding	
[38]	Chair	Count	Room	Control algorithm	Mechanical-switch sensors perform better than strain and vibration sensors; Chair sensors perform better than PIR sensors

3.6. Sensor fusion

Since the occupancy information coming from one kind of sensor may unreliable, there is a tendency for researchers to investigate the application of multiple sensors to increase coverage and extract higher levels of occupancy information that cannot be obtained by a single sensor. Sensor fusion technology usually has the ability to measure fine-grained human activities and improve the accuracy of occupancy detection based on the characteristics and advantages of different sensors. However, it does not mean that more sensors in the occupancy detection systems have better performance.

Table 4. Multi-type sensor fusion for occupancy information

Reference	Sensors	Occupancy resolution	Spatial resolution	Methodology	Remarks
[39]	PIR, keyboard, mouse, WiFi, GPS	Presence	Zone	Bayesian belief network	
[40]	CO_2, temperature, smart meter	Presence	Building	HMM	Without the need of ground truth data
[2]	PIR, keyboard, mouse, webcam	Presence	Room	Occupancy sensing algorithm	PC data can get more accurate occupancy information than PIR sensor
[41]	PIR, noise, CO_2, VOC	presence	Room	plug-and-play detection method	CO_2 sensor has the best performance when applied in a room; A combination of PIR and VOC is better for an apartment
[42]	PIR, CO_2, temperature, humidity, illumination, CO	Count, Activity	Zone	SVM, ANN, HMM	Important sensors for occupant pattern prediction are CO_2, acoustics and motion;
[43]	PIR, CO_2, double-beam, pressure mats, acoustic	Presence, count	Zone	CRF	Different combinations of sensors are evaluated in four different types of room
[44]	CO_2, energy consumption	Count	Room	CART, HMM	
[45]	CO_2, camera	Count	Room	Massive conservation equation	Cameras were used under good illumination condition, otherwise, CO_2 sensors were utilized
[46]	PIR, sound, CO_2, temperature, humidity, VOC	Count Activity	Building	ANN	
[47]	PIR, door, CO_2, electric meter	Identity, Activity	Room	Multinomial logistic regression model	Distinguish between three occupancy status of away, active, sleep
[48]	Thermal, camera	Presence, Activity	Zone	Background subtraction, ROI based segregation models	The thermal sensor overcomes the main shortcoming of PIR sensors

4. Discussion

The occupancy level at which a sensor perceives depends on how it obtains information. Take the environmental sensor as an example, since the CO_2 sensor can sense the changes of indoor CO_2 concentration, it can be used to estimate the number of occupants based on the rate at which a single occupant exhales CO_2. Economics and privacy are important measures to decide whether a program to be adopted. As can be shown in Table 5, Explicit sensors require additional devices, while implicit sensors can rely on existing infrastructure in the building. The development of computer vision technology has enhanced the ability to extract information from images, however, its invasiveness has greatly limited the application scenario.

Table 5. The characteristic of different sensor systems

Sensor type	Occupancy resolution	Infrastructure	Privacy
Motion sensors	Count	Explicit	Nonintrusive
Environmental sensors	Count	Implicit/Explicit	Nonintrusive
RF sensors	Location	Implicit	Intrusive
Camera	Activity	Implicit/Explicit	Intrusive
Contextual sensors	Count	Implicit	Nonintrusive

As can be seen from the studies reviewed, the number of occupants is most concerned by researchers in terms of occupancy levels. If take the occupant identity into account, the accumulation data of him can be applied for personalized service since an individual has a preference for the indoor environment. What's more, occupancy behavior can also be leveraged to reduce energy consumption, such as opening a window. In [49], the study reconfigured the occupant sub-areas based on similar arrival and departure times.

For different kinds of buildings, due to the defects of occupancy tracking method, the immaturity of occupied information processing method, the difference in energy consumption control methods, the control target cannot be fully realized. Thus, there is still a lot of work can be done to obtain real-time occupancy information for demand-driven building energy management.

5. Conclusion

For demand-driven building energy management, select a proper occupancy information acquisition method is the first step since different sensors have different characteristics. This paper reviews different sensor technologies based on the principle of obtaining occupancy information, and divides them into five categories, namely motion sensors, environmental sensors, RF sensors, camera, and contextual sensors. There is also a tendency for researchers to investigate the feasibility of multi-sensor fusion applications. Although great progress has been made, studies still haven't paid enough attention to the specific application environment when test the performance of sensor technologies. Besides, more robust data processing method like deep learning can be explored with the accumulation of data. To provide a more personalized service, occupancy information can be used to model the occupancy behavior characteristics.

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Approaches to improve the quality of workplace Built Environment

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Abstract

This paper highlights the main factors which can have a positive impact on the productivity of workers within an organization. It talks about the current trends and practices followed by the organizations to improve the quality of the workplace and the need to improve the quality of workplace according to changing demands of occupiers. The study is being conducted with the help of secondary research data exploring the existing work-analysis structures, trends, practices and case studies. Qualitative research methods are used for analyses of the data: Content analysis, previously published articles and papers. In this way, new ways of producing and operating buildings and the imperatives for such a process have been analysed which can help the inappropriate level of user involvement in the building procurement process and the way these buildings and work style in these buildings are managed.

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Keywords: Built Environment; Quality of Workplace; Space Management; Building Environment.

1. Introduction

In the era of exhausting natural resources, developing worldwide environmental change, corporate social responsibility & demands for ecologically friendly solutions, several organizations are progressively dedicated to developing new ways of producing & operating the building. Talking about new ways of developing a building, the decision is to create & develop green building which is not only the need of the hour but also represents a timely business decision & a good investment. In addition to other things, green buildings are considered more productive & more aesthetic for the occupants. Nowadays, organization focus on activities that ensure that the land and building asset base of an organization is optimally structured in the best corporate interest of the organization concerned, aiming to maximize human interaction with the organization. In the present era, the profession of corporate real estate and workplace encompasses business strategy for companies which is based on three important factors- that is,

I.- How and where people work,

II.- How it affects people, productivity, profit,

III.- And increasingly important - the planet.

The changing phase of the organization requires obtaining the right balance of interaction in an office environment without turning it into distraction requires a detailed understanding of work processes undertaken in the office. Thus,

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moving from the static individual process working towards more collaborative knowledge sharing. This approach requires a holistic view towards developing & maintaining the workplace, its facilities and the process of their design, construction, procurement and operation.

2. Approaches to improve the quality of the workplace by following sustainability practices

In order to improve productivity and comfort of the workplace, green buildings and increasingly green leases are addressing sustainability concerns beyond energy, water and waste.

2.1 During construction

2.2 During operation and maintenance of the building

While construction of the building is only a part of the solution for a building. Green leases give the capacity to additionally improve the environment over the course of the life of the building, while also providing benefits to both landlords & tenants who occupy them.

A Green Lease is a course of action in which both tenant and landlord agree to adopt environmentally sustainable development principles to ensure that the operation & maintenance of building reduces the negative effect on the environment and resource consumption. It intends to give motivating forces to both landlord and tenants in a commercial lease to reduce energy, water & raw material consumption, increased recycling, and also the utilization of feasible & sustainable materials in tenant improvement and provides an environment which encourages sustainable practices by both the landlord & the tenant [1].

3 Approaches to improve the quality of the workplace by following changing workstyles

There has been a declining trend towards full-time employment, increasing demand for creative minds rather than manual skills which has been refashioning our ways of working and living. Flexibility in workstyles leading to the emergence of “fluid” organizations leads to the functioning of organizations based around advice rather than instructions and decisions, the continual redefinition of tasks, encouraging “informal” and multi-strand relationships for brainstorming. A move from individuals working in cellular offices to teams of people working in an open plan environment, allowing people to interact freely, thereby supporting collaborative working. Companies now have the ability to deliver physical and virtual workplace solutions that are designed to meet the challenges of today's work styles, thus increasing the company’s competitive advantage, addresses the needs of a more diverse and multigenerational workforce, dramatically reducing costs, improving productivity, and enhancing collaboration. Many organizations presently persistently resize their CRE requirements to adjust to lower demand for physical space. Some of those approaches are-

3.1 Space Management

3.1.1 Co – working: It provides space for freelance workers. It is a shared workplace, wherein employees of different organizations can work together at the same sharing values. It provides a collaborative environment to workers from different work cultures and thus helps them in forming a synergy.

3.1.2 Open plan office: Open plan office designs are focussed on improving collaboration between the workers through improved architectural and interior designing of the office workspace.

3.1.3 Hot-desking: It is a workplace setting wherein multiple workers working for the same organization can use a single workstation at different time intervals.

3.2 Benchmarking

[2] States that “Benchmarking is the process of identifying, sharing and using knowledge and best practices”. In business, benchmarking is often about comparing processes to enhance performance. In Real Estate context, benchmarking tends to be focused on analysis of performance & seeks to examine tangible measurements, like sales/sq. mt. or total occupancy costs/sq. mt. [3] states that “Benchmarking represents a management tool for enhancing an

organization's performance & competitiveness". Factors used for comparing properties are cost per sq. ft., space per person, turnover per sq. ft., and profit per sq. ft. So, that organizations within an industry compete to provide best environment to all its stakeholders.

4 Approaches to improve quality of workplace through Facilities Management

Facilities management (FM) is a term that encompasses a wide range of activities involved in the effective management of built assets. It involves the total management of all services that support the core business of the organisation. The existence of active FM may help to identify potential problems with maintenance and running costs before they result in component breakdown and even temporary shutdown of buildings.

The facilities manager's role, as an enabler and catalyst of change, must focus on how the strategy and service mechanisms for support services can assist the business to optimise its performance. The importance of performance assessment of facilities should also be looked at as part of a broader perspective of job satisfaction issues and with particular regard to theories of motivation. [4] Identified working conditions as one of the factors that most often contribute to employee dissatisfaction at work.

[5] Identified measurement of performance as one of ``three essential issues for the effective implementation of a facilities strategy''. There is a wide range of choices in measuring facilities management performance reflecting the varied nature of the field. Benchmarking, or post-occupancy evaluation could be identified as examples [6].

5 Approaches to improve the quality of the workplace through Technology

The technology has led to a change in work processes, making workers independent of the geography of the "fixed" location building, rendering them obsolete. Freelancers, wired into the office from home or other location, via telecommuting is common nowadays. The virtual offices are one possible solution to new demands for flexibility at work.

6 Research methodology

The study approach is to a great extent based on a literature review of secondary data taken from existing work-analysis structures, trends, practices and case studies. This study analyses the domestic as well as international contemplations on factors which improve productivity and satisfaction of workers by improving the quality of the workplace. Qualitative research methods are used for analyses of the data: Content analysis, previously published articles and papers & progress done so far. The study focuses on four important aspects which are currently impacting the workplace and helping in enhancing the satisfaction and productivity of workers. These approaches are based on how green building practices, tends in workplace transformation, managing effectively the facilities of an organization and changes in technological trends enabling the workers to be more productive and also at the same time improving the quality of workplace built environment.

7 Discussion

According to U.S. Energy Information Administration (EIA) estimates that building accounts for the use of 40% of the total U.S. energy consumption in 2016, including both residential & commercial sectors, 50% of extracted natural resources, 25% of landfill waste, 10% of airborne particulates & 35% of greenhouse gases. It mainly emphasizes on the inefficiencies of conventional construction & property management practices & the necessity to adopt environmentally sustainable standards that can help minimize the contribution of building to global climate change by 70% & simultaneously benefitting both tenants & landlords, not only cutting costs & expenses required to maintain & keeps building operational but also enhancing people's working & living environments. The decision to create & develop green building is not only the need of the hour but also represents a timely business decision & a good investment.

In order to improve workplace productivity, the accommodation & workspace strategy of an organization should aim to facilitate & enhance the productivity of those work processes. In this regard, there are three categories of spaces required for workers, i.e., space to concentrate, space to collaborate and space to contemplate. The uses of these spaces are shown in Fig. below (Fig. 1)

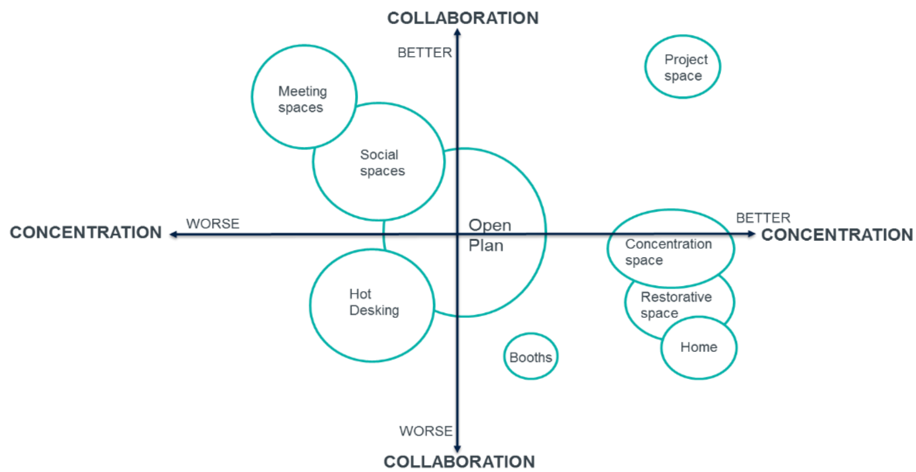

Fig. 1. Work – style analysis

Source: Corporate Real Estate Asset Management, by Barry Haynes & Nick Nunnington [7]

While technology has enabled the organization to become "global" by linking individuals and groups together irrespective of their location through tools like Skype for business, sway, networking sites like Twitter, LinkedIn etc.

It is clear that FM is an umbrella term under which a wide range of property and user-related functions may be brought together for the benefit of the organisation and its employees as a whole. Therefore, the aim of FM should be not just to optimise running costs of buildings, but to raise the efficiency and suitability of the management of space and other related assets for people and processes, in order that the mission and goals of the organisation may be achieved at the best combination of efficiency, cost and quality.

8 Conclusion and recommendations

In order to improve the quality of the workplace by incorporating sustainability during the operation and maintenance of the building and following lean principles during construction. Some of them are listed below:

I. Get your Green Building operating Program certified through the standard such as IGBC and GRIHA rating standards.
II. Make sure the lease terms are well thought through adopting smart lighting technologies such as motion sensors, timers, submetering electricity bills to reduce unnecessary use of electricity.
III. Make necessary for tenants to use Energy Star Compliant equipment & appliances (Permissibility of solar or wind applications)
IV. Water conservation measures (for example, low flow toilets, rainwater catchment, wastewater reuse, etc.)
V. Indoor air quality standards (placement of façades in the building).
VI. Recycling Programs to be adopted by tenants (example, dispose of compact fluorescent lamps in recycling containers, discard cardboard, metal, glass, paper, and plastic in assigned regions)

In order for Facilities Management (FM) to be a successful tool in improving the productivity of workers, it should aim at holistic business performance. The performance of an organization should be continually improved. Performance measurement of an organization, assessing the quality of its services through balanced scorecard as a tool should be done. Centralized FM help desk to address all Facilities management related problems across the portfolio of assets should be there which can provide services like, mapping out all customer requirements, recruiting the correct operating staff, ensuring an appropriate working environment and client communication once the help desk is operational this will enhance satisfaction of workers and clients of that organization. An integrated workplace process taking a holistic view of business, the environment and technology should be formed according to the changing needs of people (both corporate and individual), keeping in mind the management control of the process and its resulting product.

It is for these reasons [8] in his paper, "An integrated workplace process" stated that now a workplace can say to be – "Not so much a building, more a way of life".

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Assessment Of Emerging Cooling Technologies By Analyzing Their Impact On Reducing The Power Usage Effectiveness Ratio Of Data Centers

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Abstract

With the advent of high speed internet, smart-phones, Wi-Fi, Cloud computing, and IOT, our desire for creating and consuming data has been growing exponentially. It has resulted in great demand for storing and processing of this data with increase in number and scale of data center facilities around the globe. Data centers have started consuming much higher amount of power and high-performance IT equipment have presented a bigger challenge for cooling systems. Large technology companies have realized the need for making their data centers more energy efficient and, in turn, modern mechanical systems have been designed to work more efficiently. This research study endeavors to analyze these mechanical systems and present the way they affect Power Usage Effectiveness (PUE) ratios of data centers. Data from numerous data center projects carried out by a leading general contractor in last 5-years was obtained and correlation analysis was carried out to assess how modern mechanical systems help in reducing their PUE ratios.

Keywords: data; effectiveness; mechanical; power; usage

1. Introduction

One of the biggest technology revolutions the last decade brought with it was 'Big-Data' [1]. With the advent of high speed internet, smart-phones, Wi-Fi, Cloud computing, and IOT, our desire for creating and consuming data has been growing exponentially. This means a lot more space is required to store this data. Those days of having only a server room in your building to store and process this data are long gone and a new category of buildings called 'Data Center' has been established. In last 10-years, we have seen unprecedented growth in data center projects all over the world. This growth is observed both in numbers and scales of data center projects. Technological advancements in servers and other IT equipment have made these machines more compact with capabilities of handling highly complex data processing and transfer very efficiently; giving rise to higher power consumption and heat output in the same confined rack space.

Last decade also brought a lot of awareness about energy efficiency. Some of the main reasons for that were rising power costs, carbon emissions, and global warming. They have made the construction industry realize the importance of building structures that consume less energy and function more efficiently. Data Centers are one of the highest

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power consuming buildings for their size [2]. Hence, a significant amount of research is being done to reduce their overall energy needs. Mechanical cooling systems, being the largest user of energy amongst all non-IT equipment, have become the obvious choice for improving efficiency of a data center. The Green Grid, a non-profit organization specializing in data center research, introduced and promoted a metric called PUE (Power Usage Effectiveness) for measuring efficiency of data centers in 2006-07. Since then, PUE has become a globally accepted metric for establishing energy performance.

2. Literature review

The main purpose of mechanical systems in data centers is to maintain suitable environmental conditions around server racks within acceptable limits so that the heat generated from various IT equipment inside the racks can be dissipated keeping them cool. Continuous and reliable functioning of these mechanical systems is critical for any data center operation. Heating, Ventilation and Air Conditioning (HVAC) systems used in data centers that were constructed in early 2000s have been using the traditional method (Figure 1) of blowing cold air in the area which houses the IT equipment. With the development of higher power consuming IT equipment, resulting from fitting more and more transistors onto chips inside the servers and creating denser equipment, we have seen tremendous increase in rack level power use. An IT equipment rack (more commonly known as Server Rack) is a metal enclosure (cabinet) which houses various IT equipment such as servers, switches, storage devices and is usually connected to a power source above or below the cabinet. Within last 10 to 15 years the power consumption capacities of server racks have increased from 5 kilowatts (kW) per cabinet up to 25 kW and are expected to reach 50 kW in the next few years.

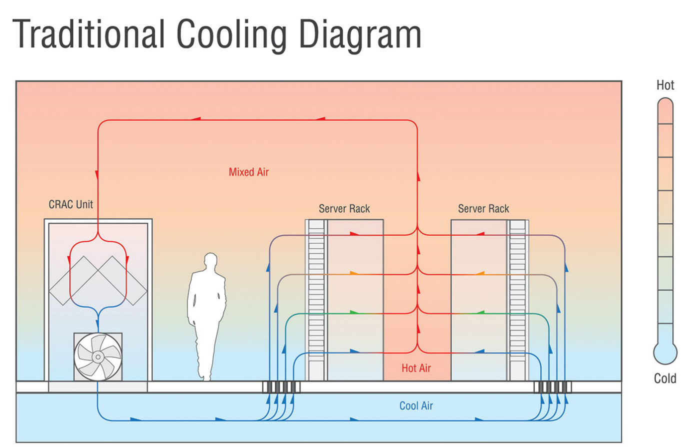

Figure 1: Traditional Data Center cooling system using raised floors.
Source: https://journal.uptimeinstitute.com/wp-content/uploads/2015/07/N-Sasser-Figure-3image2.jpeg

Free Cooling, as the name suggests, is a mechanical system that uses colder outside weather to directly cool the IT equipment space. The medium of heat transfer in this case is air, like the traditional cooling systems. However, there are two broad methods of using colder climatic conditions to supply cold air to IT rack space. First, is to directly take outside cold air and second is to use water, cooled by outside cold atmosphere. While designing and implementing this system, the engineers are first expected to ensure that the air flow management inside the data center is designed with utmost care. One of the ways to improve the air-flow and to ensure minimum mixing of hot and cold air would be to use Hot-aisle containment system. This system uses an enclosure to trap and remove hot air coming out of the rear side of racks. This stops the flow of hot air from mixing with cold air being pumped in the IT equipment space.

Direct free cooling allows outside air to pass through a series of filters in the air handling unit (AHU) before getting pumped in the IT equipment space. A significantly large assembly of filters is required to be installed for the outside air to get purified in order to maintain the indoor air quality. As this system is used in colder climates, concentration of pollutants and particulate matter is higher in cold conditions than warmer.

The second method of free cooling, indirect air-side free cooling, does not allow the outside air to mix with indoor air. A well-known example of this concept is Kyoto Wheel system [3]. It operates through air-to-air heat exchanger, which

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allows transfer of heat on a rotary heat wheel. One of the biggest advantage of indirect air-side free cooling is that it allows to maintain desirable indoor air quality (IAQ) by keeping away the pollutants and particulate matter from outside air.

IT equipment racks in data centers have different capacities of power consumption ranging from 1 or 2 kW to more than 25 kW. Higher power consumption capacities mean those racks have higher density of servers which result in to more heat output in a confined space. When these IT equipment racks start getting denser, air as a medium of heat transfer, starts becoming inefficient. In this situation Liquid Cooling, which uses water or other engineered liquids (aka Liquid Coolants) as a medium of heat transfer needs to be employed [4]. Liquid coolants are known to have better thermal properties than air. Their thermal conductivity, specific heat, and density are higher as compared to air [5].

One of the main advantages of using liquid cooling is that the temperature of liquid coolant required to be supplied to the racks is considerably higher than the temperature of air pumped in to the rack space when using conventional systems [6]. Therefore, less amount of energy is required to operate the chillers, reducing the overall energy consumption of the mechanical systems.

Liquid Immersion Cooling is the latest cooling technology which is gaining popularity in the data center industry [4]. In this system, the IT equipment is immersed in a dielectric (non-conductive) liquid such as 3M's NOVEC™ 649. The engineered fluid changes its state from liquid to gas when it absorbs heat from high-heat generating components inside the IT equipment immersed in the tank. This gas being less dense than the liquid rises to the space above the liquid. It is then taken out into a condenser which is cooled by either chilled water or another refrigerant. Through this cycle, the gas cools down, regains its liquid state and travels back to the rack space [7]. One more advantage of using liquid immersion cooling, apart from energy savings from higher allowable inlet temperature of coolant, is considerable fan energy savings and lower noise levels [4].

Direct evaporative cooling is similar to that of free cooling in configuration but totally different conceptually. Direct evaporative cooling is used in places where outside temperature is not suitable for free cooling. This cooling system is also called as adiabatic cooling which uses the cooling effect of water as it evaporates [8]. Direct evaporative cooling became Google, Facebook, Microsoft and other large technology companies' choice for their data center projects [9]. Since then, Facebook has been using DEC system on their data centers and has shown significant reduction in water usage by implementing cooling strategies specific to each location [10].

The Green Grid is a non-profit, open industry consortium of information and communications technology (ICT) industry professionals that works to improve IT and data center resource efficiency around the world. It was founded in year 2007 and right after their inception they presented the idea of Power Usage Effectiveness (PUE) metric. As simple as it sounds, this metric is a ratio of total energy required by a data center facility and the amount of energy required by the IT equipment.

$$\text{P. U. E.} = \frac{\text{Total Facility Energy}}{\text{IT equipment Energy}} \times 100\%$$

Based on the PUE formula, we can say that achieving PUE ratio of 1.0 is the best possible scenario for any data center facility. This means, no additional power is required to run the facility apart from the IT equipment. Though this scenario sounds like a utopian concept, large data center operators like Google have managed to bring down this ratio very close to 1.0 [11]. The Green Grid and Uptime institute have been recording PUE ratios of various data centers since 2007. Their initial data shows that on average the PUE ratios in year 2007 were close to 2.50 which significantly improved to 1.89 in year 2011 but by year 2014 it showed little improvement as the average reported PUE ratio was 1.7 [12]. The Environmental Protection Agency (EPA) has defined a PUE ratio of 1.5 as a 'best practice' target from year 2011 (Figure 2) for the data center industry [13]. Hence, one of the main objectives of this research was to find out if by use of emerging mechanical systems, the PUE ratios have improved in last 5-years.

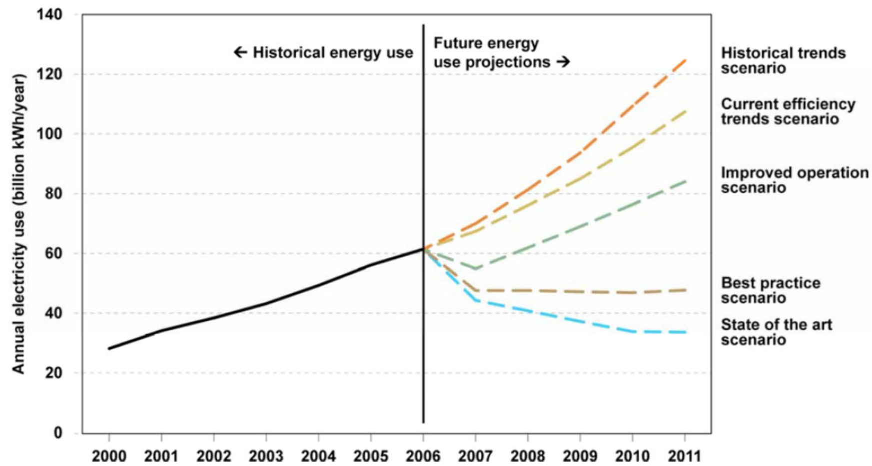

Figure 2: Comparison of projected electricity use by Data Centers (2007 to 2011) and best practice scenarios. Source: Report to Congress on Data Centers Energy Efficiency – Public Law 109-431, U.S. Environmental Protection Agency, Energy Star Program, August 2, 2007.

Weather conditions play an important role in energy consumption of the buildings. It can be easily understood that the PUE ratio of a facility will be higher in the hotter months of the year and lower in the winter. Researchers at University of Leeds, UK provided a critical analysis of the PUE metric which outlined the type of detailed engineering data required to obtain meaningful values of PUE [14]. Another study carried out at Stanford [15] showed the difference in PUE values for a hypothetical data center in 2 different cities and recommended that including weather/climate information while calculating the PUE ratios would provide a better understanding of energy efficiency.

Many operators calculate and report their facilities' PUE ratios as average of a year. Moreover, due to geographical locations of the data center facilities, the environmental conditions make significant impact on average yearly PUE values. For example, if all other factors such as infrastructure size, type, cooling technology etc. are considered equal, average PUE ratios of data centers in places like Arizona, Georgia or Florida would theoretically be higher than the facilities in Indiana or Connecticut.

A data center facility may or may not use only electricity as its soul energy source. Some facilities operate with multiple sources of energy such as electricity, natural gas, chilled water etc. Hence, in order to convert other sources of energy into electrical units – kWh, the Green Grid recommends using U.S. Source Energy Weighing Factors. To express total source energy, each fuel should first be converted into a single common unit (kWh) and then multiplied by its weighting factor, after which the source energy for all fuels can be summed together [16]. The PUE ratios mentioned in the data received for analysis are expected to have considered this conversion in calculating their power consumption of the total facility.

The PUE metric has also been critically analyzed by some researchers. Energy consumption calculations for PUE ratios are sometimes based on engineering estimates which consider full-load name-plate ratings of infrastructure components to determine efficiencies. However, if equipment is under loaded, their efficiencies decrease considerably. So, it is recommended that PUE calculations shall be based on metered data during operations [15]. PUE calculations do not consider the efficiency of IT equipment such as server configurations, their productivity, energy losses due to server idling etc. [14]. Moreover, PUE ratios are being falsely interpreted for 'Greenness' as they neither consider the sources of energy nor the carbon emissions from the facility [17]. Another important factor to be considered while ensuring accuracy of the PUE calculations, as previously mentioned, is climatic conditions. Energy consumption of IT and non-IT equipment should be recorded over a longer time span, preferably a full year. "A comparison of data centers that includes climate information and data analysis alongside the PUE would give a more comparable ranking of energy efficiency" [14].

3. Research

The design of this research is based on the research onion described by Saunders and Lewis in their book "Doing Research in Business and Management" [18]. In the first layer, we have adopted the philosophy of realism. Like other scientific enquiries, the objectivity of this research suggests that the data exists independently of our knowledge of its existence. In the next layer, we have established the approach as deductive. The author has attempted to deduce a correlation between two factors related to data center facilities viz. mechanical technologies and PUE ratios.

Layer three strategy adopted by this research falls between a survey and a case-study approach. While the data about various data center facilities was collated using the survey approach, the analysis of this data was carried out using case-study approach. The methodology adopted for this study is based on quantitative research. The data required for performing correlation analysis was based on facts and figures. Hence, quantitative research methodology was considered as the best strategy. This study focused on emerging mechanical systems, the time horizon for analyzing the data was selected as last 5-years.

Data collection parameters that were established after extensive literature review. The author acknowledged that identity of most of the data center facilities would be kept confidential. Accordingly, those parameters such as project name or exact location were kept optional. The primary objective of requesting information on locations of the facilities was to establish their climatic zones. Other parameters like PUE ratios or types of mechanical systems were considered necessary for conducting a correlation analysis.

4. Discussion

As the traditional air conditioning equipment, also known as Computer Room Air Conditioners (CRACs) or Computer Room Air Handlers (CRAHs), used cold air to cool the racks. They used the volume of space under raised floors as plenums. Perforated grills on the raised floor were then used to supply this cold air up to the racks which, after passing through the servers, became hot and got mixed with the room air and went back to the CRAC machines for cooling again. Soon after data centers started becoming bigger and denser, these traditional mechanical systems were considered as inefficient due to flaws like uneven cooling, losses as well as space and design limitations [5].

While designing the mechanical systems in last few years, engineers have tried to address most of these shortcomings that the traditional cooling methods have. Especially for large data center facilities, a slight improvement in cooling efficiency makes a big impact due to the scale at which equipment perform. Initial efforts by design engineers to improve cooling efficiencies have yielded to improvements in air-flow management within the hot/cold aisles of racks. However, in recent years some engineers have tried to change the medium of heat transfer from air to liquid, while others have tried to make use of outside cold air in favoring climatic conditions to cool the server rack space.

5. Conclusion

‘Big Data’ has made a tremendous impact on the data center industry since year 2012. We also identified that IT equipment racks, being equipped with faster processors, switches, and higher capacity storage devices, now consume large amounts of power and in turn have higher heat output in the same confined spaces. This has given rise to modern cooling technologies which now focus more on energy efficiency. Power Usage Effectiveness (PUE) is a globally accepted metric for establishing the efficiency of a data center facility by calculating the ratio of total facility energy consumption and consumption by critical IT equipment.

Data center mechanical systems that use emerging cooling technologies are evolving and getting attention of engineers and owners, especially in the large data center construction market. Free Cooling Systems, which use simple fans and small pumps consume considerably lower amount of energy, have become more popular in last 5-years. They have helped larger and denser data centers in bringing down their PUE ratios significantly closer to 1.0. Average PUE ratios have shown steady decline in their values since year 2007. However, reduction in the average PUE ratios from 2011 to 2014 was not significant. Our analysis of the data from 40 data center facilities shows that facilities using traditional mechanical systems (using compressors, refrigerants, pumps, chillers etc...) have their PUE ratios in the range of 1.5 which match EPA’s Best Practice target values. Use of modern mechanical systems on large data center facilities in the United States has significantly helped in bringing down their PUE ratios closer to 1.0

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Assessment of the Use of Delphi Technique in Sustainable Infrastructure Development Research

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Abstract

The Delphi technique over the recent decades has increasingly become generally recognized and accepted by a vast range of institutions, government departments, and policy research organizations across the globe. The Delphi method was originally developed in the 50s by the RAND Corporation (an American non-profit global policy think tank aimed at offering research and analysis to the United States Armed Forces) after a series of studies and observations in Santa Monica, California. This approach encompasses a survey conducted in two or more rounds and affords the participants in the second round with the results of the first so that they can modify the original assessments if they want to or stick to their former opinion. It is usually presumed that the method makes better use of group interaction whereby the questionnaire is used as the medium of interaction. The Delphi method is especially useful for long-range forecasting; as expert opinions are the only source of information available. The objective of this paper is to outline how the Delphi technique process was used to predict and understand issues surrounding sustainable infrastructure development in developing countries. The paper's objective is based on the premise that the technique has not been widely used to study sustainable infrastructure development, despite several empirical studies that have been conducted in its favour. This is because the Delphi approach solicits experts' views on subjects surrounded with confusion. The methodological approach adopted for the study was a content analysis of published peer reviewed journal articles with regard to the use of the technique in Sustainable Infrastructure Development studies. The Delphi technique is discussed because it is an accepted and reliable research technique that helps to resolve experts' disagreement with issues.

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Keywords: Assessment; Delphi Technique; Developing Countries; Research; Sustainable Infrastructure

1. Introduction

The Delphi technique was originally developed in the 1950s as a tool for forecasting and problem solving of complex topics at the RAND Corporation by Helmer and Dalkey [8]. The inspiration behind the naming of this technique is based on Greek mythology. The oracle at Delphi located at an ancient Greek Temple was consulted to forecast the future. This religious ritual was done to enhance accurate and timely decision making before carrying out major societal and state activities such as waging war against other States. The method adopted by the research team at RAND was that, experts of a particular subject matter could be solicited for their opinion about the likelihood of future events or

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scenarios within that same field of the subject matter. The Delphi technique is part of a group of decision-making (policymaking) techniques that includes the nominal group technique (NGT) and interacting group method (IGM). Where The Delphi technique differs in various ways from NGT and IGM, largely because it is how individual based, anonymous and independent it is.

The element of group interaction is eliminated from the technique and feedback to questionnaires is in written format [33]. According to Loo [33], the Delphi process is mostly used when investigating and drawing up policy-making or policy evaluation strategies that will set the future direction for public or private sector respectively. The thesis adopting this method was aimed at setting a future direction for sustainable infrastructure development in developing countries. Furthermore, the technique is a qualitative methodology seeking to produce a consensus of a group of experts on an issue of concern [36] through a survey consisting of rounds. The method is based on structural surveys and makes use of the intuitive available information of the participants, who are mainly experts within the discussed subject matter. The method provides qualitative as well as quantitative results and has beneath it explorative, predictive and even normative elements. There is an agreement that Delphi is an expert survey in two or more 'rounds' in which the results and findings of the second and later rounds of the survey of the previous round are given as feedback. That is, the participants who are experts answer from the second round under the influence of the other experts' opinions. Thus, the Delphi method is a relatively strongly controlled group communication process, in which matters, on which naturally unsure and incomplete knowledge is available, are judged upon by experts [20]. The technique requires knowledgeable and expert contributors individually responding to questions and submitting the results to a central coordinator or a researcher conducting the study [3]. The coordinator processes the responses, looking for central and extreme tendencies, and their validations [19]. The results are fed back to the input provided by the coordinator (researcher). The experts are then asked to resubmit their opinions, aided by the input provided by the coordinator (researcher). This process continues until the coordinator sees that a consensus has been formed. The technique removes the bias that is possible when diverse groups of experts meet together, which is common with other methods of decision making. In the Delphi method, the experts do not know who the other experts are in the process. Hence, the Standard-Delphi-Method is a survey which is directed by a coordinator (researcher) as already stated, comprising several rounds with a group of experts, who are anonymous among each other and for whose subjective-intuitive prognoses a consensus is aimed at.

After each survey round, a standard feedback about the statistical group judgement calculated from median and interquartile range of single projections is given and if possible, the arguments and counter-arguments of the extreme answers are fed back. In the Delphi process, nobody 'loses face' because the study is done anonymously using a questionnaire. Rowe and Wright [44] and Häder and Häder [20] inform that it is commonly assumed that the method makes better use of group interaction whereby the questionnaire is the medium of interaction. The method is especially useful for long-range forecasting, as expert opinions are the only source of information available [3].

Over time, the method has gained a favourable popularity across many scientific disciplines as a method of inquiry. Czinkota and Ronkainen [13] indicate that the Delphi method has gained considerable approval across disciplines. They inform that it has been used as a study instrument in the fields of library and information science [8], in the medical disciplines [30], in multi-country studies of communications in Europe, and by actuaries to predict economic conditions [48]. Czinkota and Ronkainen further report that those experienced with the Delphi technique report that the method produces valuable results that are accepted and supported by the majority of the expert community.

Similarly, in the business field, the technique has been rated highly by some as a systematic thinking tool, but has been challenged in its ability to serve as an identifier of strategic issues [50]. Mitchell [38] in the review of the use of the Delphi techniques, found in an earlier study [46] that PhD candidates that used Delphi increased from 61 (1970-1974) to 441 (1980-1984), and that they included an incredibly wide range of disciplines and topics. Hence the aim of the thesis that adopted this technique was to attract a wide spectrum of inputs from various geographically dispersed experts in Ghana, proving that the Delphi technique is well suited as a research approach and method. Delphi as a research method has had its fair share of criticism, support and debate on epistemology [39]. Notable amongst the criticism is Delphi's alleged failure to follow accepted scientific procedures, particularly, the lack of psychometric validity [46]. In response to the criticism, Coates [11] states, that if it is believed that the Delphi technique is of value not in the search for public knowledge, but in the search for public wisdom; not in the search for individual data but in the search for deliberative judgement, one can only conclude that Sackman missed the point. However, it should be noted that the approach deals with areas that do not lend themselves to traditional scientific approaches; hence Helmer [25] argues that the forecasting tendency, one of the major applications of the Delphi, is inevitably conducted in a domain of what might be called ‘soft data’ and ‘soft law’. Helmer further posits that standard operations research techniques should be augmented by judgemental information and that the Delphi method cannot be legitimately attacked for using mere opinion and for violating the rules of random sampling in the ‘polling of experts’. Such criticism Helmer argues, rest on a gross misunderstanding of what Delphi is; it should be pointed out that a Delphi inquiry is not an ‘opinion poll’. As all the above definitions illustrated, in no instance is reaching a majority opinion the ultimate goal in a typical Delphi study; it is rather the reaching of agreement. According to Buckley [5], Delphi is a tool for discovering agreement and identifying differences rather than forcing consensus. Buckley [5] further informs that: in principle, agreement alone is not a sufficient condition for arguing that Delphi is acceptable. But as with the majority of research methods, the method of use and application has an enormous influence on the eventual success of the inquiry. Hence, where no agreement develops, the Delphi still helps to clarify the issue being investigated. Thus Linestone and Turoff [30] assert that one of the common reasons for failure in a Delphi is ignoring and not exploring disagreements or points of departure. In addition to the above criticism of the Delphi technique, different authors also state different weaknesses of the Delphi Technique [29]. Notable amongst them include: It has not been shown consistently that the results from the Delphi method are any better than those achieved through other structured judgmental techniques [45]. The Delphi study is at the mercy of the worldview and biases of the coordinating or monitors team (researcher), who choose the experts, interpret the returned information and structure the questions. There is an enormous debate whether the experts should be chosen from within or outside the organization initiating the study and whether they should be experienced in the subject area of the study in question [34]. Another limitation according to Linstone [31] is on the way the process and questionnaire is structured, which Linstone believes can lead to a bias (like IQ tests), which assumes a certain cultural background. Hence, the experts may give responses they think the monitoring group wants to hear, or they may not respond at all. Consequently, the cultural background of respondents will impact upon the results. Likewise, Simmonds [51] debates that one of the key flaws in the Delphi technique is that certain questions are not asked as they do not seem important when the study begins.

Nonetheless, once the study begins, new questions cannot be added, which in turn can weaken the study considerably. Also, Lang [29] states that the process of choosing the panelists or expert participants is often not considered thorough enough. Yet, it is the calibre of the panelists that determines the quality of the outcomes of the study [29]. A major consideration was given to this particular criticism; hence a list of criteria was set for the panelist to fulfill. In the process of achieving consensus, extreme points of views run the risk of being suppressed, when in fact they may provide important new information or insights [29]. The flexibility of the technique means it can be adapted to a whole range of situations that in turn can make it vulnerable to misrepresentation and sloppy execution. Amara [4] found that the Delphi technique can be extremely sensitive to: the level of panelists’ expertise; the composition of the panel; clarity of the questions; the way the research or coordinator reports reasons for outliers and the administration of the questionnaire. Despite the limitations noted above from different scholars, Brill et al. [7] describe the Delphi as a particularly good research method for developing consensus among a group of entities having expertise on a particular topic where information required is subjective and where participants are separated by physical distance [30]. Brill et al. [7] further state that the Delphi method has been validated in the literature as a reliable empirical method for consensus reaching in a number of areas. Amongst these areas include distance education [54], journalism [53], visual literacy [7], electronic commerce [1], health care [55] and others. Beside these areas, the method has also been used in many other disciplines such as in information technology (IT) research to identify and rank key issues for management attention [15, 27] scientific study of GIS [23], quality management [47], terrorism [40], banking [5], social sciences [28], privatization of utilities [12], education [57], amongst others.

The above instance proves that the Delphi method in research is an accepted practice. However, as discussed above, it is not entirely appropriate for all research activities. Consequently, the objective of this paper is to assess how the Delphi technique was used to predict and understand issues surrounding sustainable infrastructure development in developing countries. This was done in order to determine the criteria and indicators that influence successful sustainable road infrastructure project implementation in developing countries. The paper describes the Delphi technique by investigating its advantages and disadvantages, before illustrating the process of execution. The paper commences by describing the technique through an investigation of its advantages and disadvantages, before illustrating the process of execution. This was followed by a brief statement on the epistemological approach of the

Delphi techniques for the study; when to use the method; components of the techniques and the process of execution of the technique for the referenced study.

2. Epistemological Approach towards the Delphi Design

The differences amongst the various group techniques and the definition of the Delphi method as identified by various scholars, as well as acknowledgment of the various criticisms, forms the epistemological foundation for defining the approach towards a typical Delphi study design. Amongst these include reducing the effects of personal bias. This is done by ensuring that all expert feedback is anonymous. Through this, the technique captures the opinions, experience, and knowledge of each expert participant. Personal knowledge is harvested and interpersonal interaction biases are stripped away. According to Scheele [49], the concreteness of the framework of the Delphi technique is vital in researching the overall objective of the study. The basic premise of the Delphi research technique towards a typical sustainable infrastructure development study, is entrenched in some form of general agreement and consensus regarding the core ingredients and components of the subsequent framework. Given the current status of implementing sustainable development in infrastructure development in developing countries, and the absence of generally agreed upon sustainable infrastructure development issues, the search for consensus and a point of departure in issues on sustainable infrastructure development policy that will better serve developing countries is therefore justified through the use of this technique.

Hence the objective of the Delphi design for this study is to obtain the most reliable consensus of opinions of a group of experts in the specific field being studied. According to Lang [29], the Delphi technique is mostly used to solicit the opinions of experts to determine the timing and possible occurrence of future events. It is a method that is best used where there is little past data available to generalize from, and where social, economic, ethical and moral considerations are pre-eminent. Considering the outcome of a literature review of the current research (there is no structured research so far carried out which has adopted the technique with regard to a sustainable infrastructure development study in a developing country) and definition, function and nature of Delphi technique, it is justified that, Delphi technique was the best method to explore the subject of the research and to achieve the aims and objectives.

3. When to Use the Delphi Technique

The Delphi method is mostly used when long-term issues have to be assessed such as the subject of the current research. This is mainly due to its procedural outlines used to identify statements (topics) that are relevant for the future; it reduces the tacit and complex knowledge to a single statement and makes it possible to judge upon [18]. Hence, its use in combination with other methodologies like survey design can be interesting. On the other hand, it is applicable in more complex issues, when the themes cannot be reduced that much or when thinking and discussions in alternatives are the major target. It is also suitable if there is the (political) attempt to involve many persons in processes [17]. Hence, Linstone and Turoff [32] argue that one or more of the following properties could lead to the need for the use of the Delphi technique: when the problem of inquiry does not lend itself to precise analytical techniques but can benefit from subjective judgments on a collective basis [9]; when the research needs to contribute to the examination of a broad or complex problem with no history of adequate communication and may represent diverse backgrounds with respect to experience or expertise, which was a major premise of the research; when more individuals are needed than can effectively interact in a face-to-face exchange; when time and cost to make frequent group meetings is limited; when the efficiency of face-to-face meetings can be increased by a supplemental group communication process; when disagreements among individuals are so severe or politically unpalatable that the communication process must be refereed and/or anonymity assured; when the heterogeneity of the participants must be preserved to assure validity of the results, such as the avoidance of domination by quantity or by strength of personality called the "bandwagon effect".

According to Grisham [19], the Delphi method as a foresight tool seems to possess certain degrees of invariance to survive in the changing challenges of the past 50 years. Hence, the process could serve different understandings of prediction or premonition and is probably understood by the users as being relevant for covering technical perspectives, organizational perspectives, and personal perspectives. Grisham [19] further emphasizes that what the users of the Delphi technique especially like, are the sets of data about the future that are collected. Writing down future topics seems to have an immense psychological effect because it transfers implicit to tacit knowledge to the more visible, explicit, and therefore transferable knowledge [19].

4. Research Methodology

The research was conducted with reference to existing theoretical literature, published and unpublished literature with a deep exploration of their context in order to meet the research objectives. The study is mainly a literature review and looks at how the Delphi technique can be used to predict and to understand issues surrounding sustainable infrastructure development in developing countries. This is presented through the discussion of how the Delphi technique was employed in the study. This approach was adopted to overcome the confusion surrounding the constructs that influences successful implementation of sustainable road infrastructure projects in developing countries, because the Delphi approach solicits experts' views on issues in a systematic approach.

5. Components of the Delphi Technique

The main components of the Delphi technique according to Loo [33], consists of five major characteristics, which was also adopted in the study: The study should consist of a panel of carefully selected experts representing a broad spectrum of opinion on the topic or issue being examined; the participants are usually anonymous; the coordinator (researcher) constructs structured questionnaires and feedback reports for the panel over the course of the Delphi; it is an iterative process often involving three to four iterations called 'rounds' of questionnaires and feedback reports; there is an output, typically in the form of a research report containing the Delphi results, the forecasts, policy and program options (with their strengths and weaknesses),recommendations to senior management and possibly an action plan for developing and implementing the policies. Likewise, Hasson et al. [22] recommended that the following research guidelines for using the Delphi technique be addressed in designing a Delphi approach: Research problem identification; Understanding the process; Selection of experts;

Informing /invitation to experts; Data analysis; and Presentation and interpretation. Therefore, given the nature of the research, it was further believed that the Delphi technique is well suited to obtain credible inputs from experts in industry, academics, government and NGOs to serve as key input towards the research objectives. The next sections provide an overview of how the Delphi technique was used in this study.

5.1 Designing, Constructing and Executing the Delphi

Given the rationale behind the Delphi technique and the main features explained above, the design, construction and execution of the Delphi study for the current research followed a sequential process as suggested by Loo [33]. According to Loo, four vital planning and execution activities were to be followed, which are: Problem definition; Panel selection; Determining the panel size; and Conduction of the Delphi iterations. Supporting Loo's [33] approach, Delbecq et al. [15] suggest a basic Delphi methodology that includes distinct stages such as, Delphi question development (objective), expert panel selection, sample size, first questionnaire, first questionnaire analysis and follow-up questionnaires. This methodology forms the basis of the research study and is explained in the subsequent sections.

Stage 1 - Delphi question development

The formulation of the Delphi question is vital to the whole process. It is paramount that the panel of experts understand the broad context within which the questionnaire is designed. In order to achieve the objectives of the study, key questions were asked. The foundation for constructing the questions for this study was based on the guidelines given in Table 1, with corresponding wording and phrasing given for this study.

Table 1: Delphi question formulation

Key Delphi questions?	Phrasing for this study
Why are you interested in this study?	This study was initiated because of the belief that there is no holistic framework to guide the implementation of SRIP in developing countries. This assumption is solid because there is a discrepancy about the criteria and indicators that determine successful SRIP implementation.
What do you need to know that you do not know now?	Despite the existence of some frameworks for sustainable infrastructure project implementation, these are not comprehensive and do not capture all the requisite features.
	The criteria and indicators that will determine successful SRIP implementation will come out clearly at the end of this study.
How will the results from the Delphi Study influence Sustainable Road Infrastructure Project Implementation?	The results of the Delphi Study will enable the development of a conceptual framework for the SRIP implementation framework to be developed. The criteria that would collectively predict and assure successful SRIP implementation framework will be established.

Stage 2 – Delphi Expert Panel Selection

A critical part of conducting a Delphi interview technique is selecting the right experts (also known as panellists, participants or respondents) and their role is crucial to the success of the research [22]. Experts must be sufficiently interested and involved in the subject being examined to ensure high commitment response rate. According to Hasson et al [22], controversial debate rages over when a professional becomes an 'expert'. The claim that one group represents valid expert opinion has been criticised as scientifically untenable and overstated [22]. For the purpose of this research McKenna's [35] definition of 'expert' as being a panel of informed individuals otherwise called experts hereafter was used. McKenna's [35] definition was further supported by Goodman [18] stating that the Delphi technique "tends not to advocate a random sample of panelists, instead, the use of experts or at least of informed advocates is recommended". Likewise, Helmer [24] argues that since a "Delphi inquiry is not an opinion poll, relying on drawing a random sample from the population of experts is not the best approach, rather, once a set of experts has been selected (regardless of how – but following a predetermined qualifying criteria), it provides a communicative device for them that use the conduct of the exercise as a filter in order to preserve anonymity of responses" which is core to the Delphi technique. Therefore, Linstone [32] states that the most significant danger in selecting the panel of expert lies in the path of 'least resistance' through the selection of a group of cosy friends and / or like-minded individuals, which thus negates the strength of the process. Panellists form the cornerstone of the Delphi technique and clear inclusion criteria should be applied and outlined as a means of evaluating the results and establishing the study's potential relevance to other settings and populations [26]. According to Dalkey and Helmer [14], there are detailed criteria for the selection of panel experts; recommending that in a typical Delphi study, experts should meet the following two recommendations which were also postulated by Rodgers and Lopez [43]. The first recommended criterion is that the experts should exhibit a high degree of knowledge or experience in the subject matter. Another criterion is that they should be the representatives of profession so that their suggestions may be adaptable or transferable to the population. Similarly, Adler and Ziglio [2] stated that the Delphi participants in any study should meet four "expertise" requirements, which are: knowledge and experience with the issues under investigation; capacity and willingness to participate; sufficient time to participate in the Delphi; and effective communication skills. In choosing panellists for this study, each expert was required to meet at least five of the following minimum criteria:

Residency: Have lived or is living within one of Ghana's Metropolis, Municipality or District; at least more than one year; Knowledge: Has knowledge of infrastructure development and Sustainable development; Academic Qualification, has been presented an earned degree (National Diploma/B-Degree/M-degree/PhD) related to any field; Experience: Has a history of currently is performing consultation services for Ghana's organ of State, individuals, businesses, agencies, companies, and/or organizations, relating to infrastructure development or other sustainable development context. Employment: Currently serves (or has previously served) in a professional or voluntary capacity (e.g., at place of employment - institution, business, agency, department, company) as supervisor or manager of establishment that is involved with infrastructure development or sustainable development related issues in Ghana;

Recognition: Has served / currently is serving as a peer-reviewer for one or more manuscripts received from a journal editor prior to its publication in the primary literature, with focus of the manuscript(s) on infrastructure development or sustainable development; Authorship: Is an author/co-author of peer-reviewed publications in the field of infrastructure development with emphasis on developing countries; Research: Has submitted one or more proposals to or has received research funds (grant/contract) from national, local government, regional, and/or private sources that support infrastructure development and sustainability in developing countries;

Teaching: Has organized, prepared, and successfully presented one or more infrastructure development or sustainable development training workshops focusing on the group for which expertise is sought; Membership: Member of a professional body. Should be the representative of a professional body so that their opinions may be adaptable or transferable to the population;

Willingness: Panel members must be willing to fully participate in the entire Delphi studies. The adoption of five criteria was considered stricter than the recommended number of at least two criteria by Rodgers and Lopez [43] and Dalkey and Helmer [14]. The five minimum criteria were framed after the four recommendations made by Adler and Ziglio [2], with the inclusion of experts' residency status, which was considered to be compulsory for all selected experts. Also, a minimum number of five criteria were set because the method may be undermined if panellists are recruited who lack specialist knowledge, qualifications and proven track records in the field amongst others. Although of course expertise comes in many guises and may include those who are 'experts by experience' [21]. In general, a varied panel is considered best in producing a credible Delphi study and individuals who might provide a minority or differing perspective should be actively recruited to the panel [32], which was adopted for the study. With regard to the recruitment process itself, panellists were recruited via e-mail, with a brief overview of the study objective. Thereafter, those that consented to the preliminary invitation were sent a detailed description of the Delphi study. Hence all experts selected for the current study met the five criteria set for the study. After the verification exercise, selected experts were then sent the first round questionnaire survey that was presented in the form of both closed and open-ended questions.

Stage 3 – Determining the Panel Size

Since the nature of the Delphi technique calls for a qualitative rather than a quantitative approach, the use of experts for input indicates that the number of participants should be expected to be much lower than normal quantitative surveys. Determining the minimum number of experts to participate in a typical Delphi survey has been a subject of debate overtime. Various scholars have recommended different sample sizes. For instance, Darkey and Helmer used a panel of seven experts in their original Delphi experiment in 1953 [23]. Linstone [31] finds that "a suitable minimum panel size is seven". Linstone justified this by saying that the research runs the risk of accuracy deteriorating rapidly as number increases. Hence Linstone's observation was supported by Cavalli-Sforza and Ortolano [10] who postulated that a "typical Delphi panel has about eight and twelve members", while Phillips [41] also informs that the optimum number of participation should be between seven and twelve members both citing the same reason as Linstone. Miller [37] refers to the economics of scale in large groups of Delphi surveys. Miller assumes that beyond the first thirty responses, additional responses do not generate much new information. Similarly, Dunn [16] suggests a ten to thirty participants, apprising that as the complexity of the policy issue increases, the sample size needs to be larger to include the entire range of participants both for and against the policy issue area.

According to Aigbavboa and Thwalla [3], if the group of experts is fairly homogeneous (sharing similar opinions) then ten to fifteen panelists will be enough and if there are diverse interests present among the experts, then the size of the group will need to be increased to ensure balance [58]. Skulmoski, Hartman and Krahn [52] highlighted a number of factors that should be considered in order to determine sample size for a Delphi technique: Heterogeneous or homogeneous sample [15]; Decision quality/Delphi manageability trade off [32]; Internal or external verification. Therefore, a sample size of 15 panellists was adopted based on the following premise in conjunction with the qualifying criteria's as established in stage two of the Delphi study which are: Experts should have a fair and practical split between academics and practitioners; Panellist in both categories should have an extensive experience relating to infrastructure development and sustainable development context. Beside the above criteria, the current study also adopted Rowe, et al [45] recommendations that the resultant selected participants should represent a wide variety of backgrounds to guarantee a wide base of knowledge and experience. The adopted experts' number of 15 seems appropriate, given the amount of data and subsequent analyses each panellist generates.

Stage 4 – Conducting the Delphi Iterations

Sequences of questionnaire rounds are used to obtain iterative responses to issues in a Delphi study [3]. For instance, Woudenberg [56] proposes two or ten rounds as appropriate numbers of rounds, supporting the assertion that accuracy is expected to increase over rounds, because of the repetition of judgement and group pressures for conformity. Likewise, Critcher and Gladstone [12] suggest between two and five rounds. The Delphi study for the research consisted of three rounds. In average, each round took about a month to be completed. A questionnaire was designed for each round based on responses to the previous one. Round one's questionnaire was designed based on a summary of the comprehensive review of literature highlighting sets of criteria and indicators that are potentially relevant to the implementation of sustainable road infrastructure projects in developing countries. These were structurally and constructively put together to frame the first round of the Delphi survey. Closed and open-ended questions were used in this round; thereafter, this was analysed and formed the basis of round two and three of the study. Frequencies were obtained to measure the degree of consensus reached amongst participants regarding the criteria, indicators that influence successful implementation of sustainable road infrastructure projects in developing countries and for other related questions. Also, content analysis methodology was adopted to analyse responses to the open questions to "minimise redundancy" [3] The purpose of the second round of the study was to allow experts to review and comment on the criteria and indicators that influence successful implementation of sustainable road infrastructure projects in developing countries, which were proposed by expert participants in round one. Closed and opened questions were used in this round to investigate participants' comments, expressing agreement, disagreement or clarification concerning proposed criteria and indicators that influence successful implementation of sustainable road infrastructure projects.

The specific nature of the closed-ended questions stimulated participants' reactions. Frequencies were likewise obtained to measure the degree of consensus reached amongst participants. Furthermore, content analysis approach was adopted to analyse responses to the open questions. The final round was specifically designed to: Inform the experts of the findings of the analysis of responses to the questionnaire of round two; request their final affirmation / comments on attributes and issues that did not receive any consensus in round two. The questionnaire of round three was designed based on the findings of content analysis and measures of frequencies responses to the questionnaire of round two. Closed and opened questions were also used and frequencies were obtained to indicate consensus reached among experts regarding criteria and indicators that influence successful implementation of sustainable road infrastructure projects issues as presented in the study. Where consensus was not reached, the reasons for the disagreements were noted and reported in the findings section of the study.

Over the three round Delphi survey, consensus was reached regarding most of the criteria and indicators that influence successful implementation of sustainable road infrastructure projects in developing countries. Based on the findings of the analyses of responses to the Delphi rounds, a list of criteria and indicators that influence successful implementation of sustainable road infrastructure projects was prepared which informed the conceptual framework for the broader study, while issues surrounding sustainable road infrastructure project implementation in developing countries were highlighted which responded accordingly to the set objective of the Delphi study. The Delphi survey was conducted via electronic mail, and follow-up emails were used to encourage prompt responses to the questionnaires.

6. Conclusion

The paper deliberated on the Delphi technique as an accepted and reliable research technique, with participants or expert panel members responding to a series of questionnaires (three rounds) to achieve a consensus in identifying the criteria and indicators that influence successful implementation of sustainable road infrastructure projects in developing countries. The technique was adopted as a preliminary investigation into the wider quest to determine the criteria and indicators that influence successful implementation of sustainable road infrastructure projects because it is intended to remove the bias that is possible when diverse groups of experts meet together which is common with other methods of decision making. Therefore, based on the premise of the outlined process, it is recommended that when the Delphi technique is to be adopted as a research tool for sustainable infrastructure development studies, the questions for the experts should be well formulated because questions are vital to the whole process. It is also paramount that the panel of experts understand the broad context within which the questionnaire is designed. Also, in the selection of experts, strict measures should be adopted that will not compromise the process. Likewise, in determining the panel size, it should be ensured that selected participants represent a wide variety of backgrounds to guarantee a wide base of knowledge and experience.

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Clients and construction health and safety (H&S)

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Abstract

Contractor H&S is influenced directly and indirectly by clients. Furthermore, traditionally, worldwide, better practice client organisations have maintained rigorous contractor H&S management programmes and contributed to contractor H&S.

Given the above, a self-administered questionnaire survey was conducted among developer members of the South African Property Owners Association's (SAPOA) to determine construction H&S perceptions and practices.

Findings include: clients view the traditional project parameters of time, quality, and cost as more important than public H&S and project H&S; client organisations can be deemed to have influenced and contributed to contractors' H&S relative to a range of interventions / requirements; clients appoint agents to fulfil their function in terms of the Construction Regulations; a range of design, procurement, and construction aspects impact on H&S; a range of benefits accrue from client contributions to contractor H&S; clients contend that they have influenced construction H&S, and that they could influence construction H&S more, and a range of design, procurement and construction aspects / interventions can contribute to an improvement in construction H&S.

Conclusions include that clients do influence construction H&S and that multi-stakeholder benefits accrue there from, and that clients can further contribute to construction H&S. Furthermore, the client related requirements of the Construction Regulations are underscored by the findings.

Recommendations include that property and other built environment tertiary education related programmes should address construction H&S, and SAPOA and other professional associations should evolve construction H&S practice notes.

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Keywords: Clients; Construction; Health and Safety

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1. Introduction

The report 'Construction Health & Safety Status & Recommendations' highlighted the considerable number of accidents, fatalities, and other injuries that occur in the South African construction industry [1]. The report cited the high-level of non-compliance with H&S legislative requirements, which is indicative of a deficiency of effective management and supervision of H&S on construction sites as well as planning from the inception / conception of projects within the context of project management. The report also cited a lack of sufficiently skilled, experienced, and knowledgeable persons to manage H&S on construction sites.

Within the context of South Africa, the Construction Regulations promulgated in July 2003, and amended in 2014 [2], effectively included client responsibility for construction H&S. Given this a study was conducted to assess clients' construction H&S perceptions and practices, the primary objective of the study being to determine the role of clients in contractor H&S and their influence thereon. The secondary objectives of the study being to determine the:

- Importance of project parameters to client organisations;
- Extent to which client organisations influence and contribute to contractors' H&S;
- Extent to which various aspects negatively impact on construction H&S;
- Extent to which respondents' organisations have influenced construction H&S, and the extent to which it could influence construction H&S;
- Extent to which benefits have resulted from clients' contributions to contractor H&S, and
- Extent to which various aspects / interventions can contribute to an improvement in construction H&S.

2. Review of the Literature

2.1. Compliance and non-compliance

According to the Construction Industry Development Board (cidb) [1], during August 2007, the Department of Labour inspectorate conducted inspections throughout South Africa. 1 415 construction sites were visited and 52.5% of the contractors were found to be non-compliant with the Occupational Health & Safety Act and the Construction Regulations. Of the 1 388 notices issued by inspectors, 86 (6%) were improvement notices, 1 015 (73%) were contravention, and 287 (21%) were prohibition. These findings indicate contractors in general are not complying. Furthermore, they underscore the rationale for client responsibility for construction H&S in terms of the Construction Regulations and the moral need for clients to contribute to construction H&S.

2.2. Cost of Accidents (COA)

The cidb [1] refers to Smallwood's 2004 findings that the total COA could have been between 4.3% and 5.4%, based upon the value of construction work completed in South Africa in the year 2002. The key issue relative to the COA is that ultimately, clients incur the COA as the COA is included in contractors' cost structures, and therefore constitutes a motivator to clients to contribute to construction H&S.

2.3. Recommendations and legislation pertaining to clients

The International Labour Office (ILO) [3] states clients should:

- Coordinate or nominate a competent person to coordinate all activities relating to H&S on their construction projects;
- Inform all contractors on such projects of special risks to H&S that they are aware of, and
- Require tenderers to make provision for the cost of H&S measures during the construction process.

The Construction Regulations [2] require a range of client interventions relative to contractors. In terms of information they must prepare and provide Principal Contractors (PCs) with H&S specifications, and any information that may affect H&S. In terms of procurement they must ensure that PCs have made provision for the cost of H&S in their tenders, that they are competent, have the necessary resources, have workers' compensation insurance cover, and they must appoint them in writing. In terms of planning and controlling, they must discuss the contents of and approve the H&S plan, which is the PC's response to the H&S specification, ensure that the PC implements and maintains the H&S plan, and stop work not in accordance with the H&S plan. Therefore, clients are legally required to become directly and indirectly involved in, and to contribute to contractor H&S. However, clients may appoint an agent in terms of the responsibilities, but the agent must be registered, competent, and have the necessary resources to fulfill the function of agent.

2.4. Client actions

A model evolved by Huang and Hinze [4] indicates that clients influence project H&S through: communicating H&S; selection, and participating in H&S management. Communicating H&S includes setting the project expectations for every party involved through the contract and other communications. Selection includes the: selection of contract type and arrangement; project design; project schedule; construction methods; selection of designers, contractors, and subcontractors, and decisions regarding outsourcing and vendors. Participating includes: H&S program; H&S orientation; H&S observations; H&S inspections; accident investigations; H&S recognition; H&S enforcement; drug testing; job H&S analysis, and H&S plan review.

The Australian Federal Safety Commissioner's best practice client H&S principles emphasises client involvement in and contributions to contractor H&S [5]: developing an H&S culture in their own organisations and across the construction industry by including H&S as an integral aspect of project management; affording H&S status equal to that afforded cost, quality, and time; providing leadership and commitment by considering H&S at every level of decision making; referring to H&S standards in contracts; monitoring H&S throughout all stages of projects; communicating H&S information to all project stakeholders in the supply chain, and managing H&S hazards and risks, and maintaining effective H&S measures across the project lifecycle. This in turn requires regular H&S reporting using both 'leading' and 'lagging' H&S indicators, the conducting of project completion reviews that address H&S, and monitoring and evaluating H&S performance through Key Performance Indicators (KPIs) to measure performance against industry, organisational, and project benchmarks.

2.5. Benefits of client involvement

According to the Health & Safety Executive (HSE) [6], where clients demand high H&S standards on their projects, these are achieved, and argue that there are good business and ethical reasons for clients to be committed to H&S. Accidents may implicate clients and result in delays. Furthermore, unhappy workers produce defective work, and ultimately clients pay for all the resultant unavoidable waste.

Hinze [7] cites a specific case study involving a large public sector client in the USA, which client made a dramatic change in the H&S performances of its contractors in a period of just two years. Although the client was proactive relative to H&S, they were possibly not as proactive as they could have been. Further, although the H&S performance of the contractors on the client's projects was regarded as respectable given an average recordable injury rate (RIR) of 4.2, as a result of a fatality on a project the client met with contractors to express their H&S expectations. The primary changes made by contractors included increased worker H&S training, increased supervisor H&S training, random drug testing, bolstered H&S staffing of projects, more detailed accident investigations, and a stronger focus by the client on subcontractor management. Furthermore, the client required the top managers of the contractors to show their commitment to H&S and to indicate the importance of H&S within the organisations. As a result of these interventions the RIR dropped from 4.2 to 2.34.

3. Research

3.1. Research method and sample stratum

The sample stratum consisted of members of the South African Property Owners Association (SAPOA). 75 Members that undertook developments were surveyed using a self-administered questionnaire. The questionnaire consisted of twelve closed-ended questions. Nine of the questions required responses to a five-point Likert type scale, one required a 'Yes' or 'No' response, one required the selection of possible approaches, and one required the provision of data. Two members responded stating that they were not involved with development, and two questionnaire surveys were returned to the sender as they could not be delivered. 13 responses were included in the analysis of the data, which constitutes a net response rate of 18.3%: 13 / (75 – 4).

3.2. Research findings

Table 1 indicates the importance of seven parameters to clients in terms of percentage responses to a scale of 1 (not important) to 5 (very important), and a mean score (MS) ranging between 1.00 and 5.00. It is notable that the MSs are all above the midpoint score of 3.00, which indicates that in general the respondents can be deemed to perceive the parameters as important. However, given that the MSs for the top six parameters are > 4.20 ≤ 5.00, the respondents can be deemed to perceive them to be between more than important to very important / very important. It is notable that all three of the traditional project parameters, are ranked within the top three, the implication being that clients are likely to focus on these parameters, particularly when faced with challenges relative thereto. Construction ergonomics falls within the range > 3.40 ≤ 4.20 – between important to more than important / more than important.

Table 1. Importance of project parameters to respondents' organisations.

Parameter	Response (%)						MS	Rank
	Un-	Not…………..…………………..Very						
	sure	1	2	3	4	5		
Project time	0.0	0.0	0.0	0.0	15.4	84.6	4.85	1
Project quality	0.0	0.0	0.0	7.7	7.7	84.6	4.77	2
Project cost	0.0	0.0	0.0	0.0	30.8	69.2	4.69	3
Public H&S	0.0	0.0	7.7	7.7	7.7	76.9	4.54	4
Project H&S	0.0	0.0	7.7	0.0	30.8	61.5	4.46	5
Environment	0.0	0.0	0.0	23.1	30.8	46.2	4.23	6
Construction ergonomics	0.0	7.7	0.0	7.7	76.9	7.7	3.77	7

Table 2 indicates the extent to which respondents' organisations influence and contribute to contractors' H&S relative to twenty-three interventions / requirements in terms of percentage responses to a scale of never to always, and a MS ranging between 1.00 and 5.00. It is notable that nineteen of the MSs are above the midpoint score of 3.00, which indicates that in general the respondents' organisations can be deemed to have influenced and contributed to contractors' H&S relative to the interventions / requirements. However, given that the MSs for the top seven interventions / requirements are > 4.20 ≤ 5.00, the respondents can be deemed to perceive the influence and contribution to be between often to always / always. However, 'require a project H&S plan of contractors', 'provide a project H&S specification to contractors', and 'ensure contractor's registration for compensation insurance' are requirements of the Construction Regulations. Although clients are also required to ensure that contractors have made adequate financial allowance for H&S, 'require inclusion of an H&S section in the Bill of Quantities / contract documentation' constitutes best practice. 'Require a contractor H&S management system' also constitutes best practice. 'Specify materials i.e. instruct designers' and 'conduct constructability reviews of design' are notable rankings as they indicate client focus on design related issues that influence H&S. The interventions / requirements ranked eighth to fifteenth have mean scores > 3.40 ≤ 4.20, which indicates that respondents can be deemed to perceive the influence and contribution to be between sometimes to often / often. ‘Provide contractor H&S guidelines’, ‘contractor H&S coordinator’, ‘provide H&S induction’, and ‘require attendance of client H&S meetings’, constitute direct client H&S interventions and best practice. ‘Review designer design and construction method statements’ indicates client focus on a design related intervention that influences H&S and which is also a requirement of the Construction Regulations. ‘Require risk assessments’, ‘require method statements’, and ‘require safe work procedures (SWPs)’ are requirements of the Construction Regulations. The interventions / requirements ranked sixteenth to twenty-first have mean scores $> 2.60 \leq 3.40$, which indicates that respondents can be deemed to perceive the influence and contribution to be between rarely to sometimes / sometimes. Ensure adequate contractor financial allowance for H&S’ is a requirement of the Construction Regulations. ‘Review contractor H&S meeting minutes’, ‘require permit to work’, ‘require employee identification’, ‘pre-qualify contractors on H&S’, and provide H&S training to contractors. Twenty-second ranked ‘require MSDSs’ has a mean score $> 1.80 \leq 2.60$, which indicates that respondents can be deemed to perceive the influence and contribution relative thereto to be between never to rarely / rarely, and relative to twenty-third ranked provide H&S incentives to be between never to rarely. MSDSs are required in terms of the Regulations for Hazardous Chemical Substances and ‘provide H&S incentives’ is a client best practice intervention.

Table 2. Extent to which respondents’ organisations influence and contribute to contractors’ H&S.

Intervention / Requirement	Response (%)						MS	Rank
	Unsure	Never	Rarely	Some-times	Often	Always		
Require a project H&S plan of contractors	0.0	0.0	0.0	7.7	0.0	92.3	4.85	1
Require inclusion of an H&S section in the Bill of Quantities / Contract documentation	0.0	0.0	7.7	0.0	7.7	84.6	4.69	2=
Require a contractor H&S management system	0.0	0.0	0.0	7.7	23.1	69.2	4.62	2=
Provide a project H&S specification to contractors	0.0	0.0	7.7	7.7	23.1	61.5	4.38	4
Specify materials i.e. instruct designers	0.0	0.0	0.0	15.4	46.2	38.5	4.23	5=
Conduct constructability reviews of design	0.0	0.0	7.7	7.7	38.5	46.2	4.23	5=
Ensure contractors’ registration for compensation insurance	0.0	7.7	7.7	7.7	7.7	69.2	4.23	5=
Provide contractor H&S guidelines	0.0	0.0	23.1	0.0	23.1	53.8	4.08	8
Contractor H&S Coordinator	0.0	7.7	7.7	7.7	30.8	46.2	4.00	9=
Require risk assessments	0.0	15.4	0.0	7.7	23.1	53.8	4.00	9=
Review designer ‘design and construction’ method statements	0.0	0.0	7.7	23.1	46.2	23.1	3.85	11=
Provide client H&S induction	0.0	7.7	23.1	0.0	15.4	53.8	3.85	11=
Require method statements	0.0	0.0	15.4	30.8	23.1	30.8	3.69	13=
Require safe work procedures (SWPs)	7.7	7.7	7.7	7.7	23.1	46.2	3.69	13=
Require attendance of client H&S meetings	0.0	15.4	15.4	7.7	23.1	38.5	3.54	15
Ensure adequate contractor financial allowance for H&S	7.7	15.4	7.7	7.7	23.1	38.5	3.38	16
Review contractor H&S meeting minutes	0.0	15.4	15.4	30.8	7.7	30.8	3.23	17
Require permit to work	7.7	15.4	15.4	15.4	7.7	38.5	3.15	18
Require employee identification	0.0	23.1	15.4	23.1	7.7	30.8	3.08	19
Pre-qualify contractors on H&S	0.0	30.8	23.1	0.0	15.4	30.8	2.92	20
Provide H&S training to contractors	0.0	30.8	30.8	7.7	0.0	30.8	2.69	21
Require material safety data sheets (MSDSs)	7.7	38.5	7.7	15.4	23.1	7.7	2.31	22
Provide H&S incentives	7.7	53.8	30.8	0.0	7.7	0.0	1.46	23

84.6% of respondents’ organisations appoint agents to fulfill their function in terms of the Construction Regulations. 7.7% were unsure and 7.7% meet the requirements through in-house personnel and agents. This finding indicates that clients are likely to lack the requisite competencies.

Table 3 indicates the extent to which twelve aspects negatively impact on construction H&S in terms of percentage responses to ‘does not’ and a scale of 1 (minor) to 5 (major), and a MS ranging between 0.00 and 5.00. It is notable that 11 / 12 (91.7%) MSs are above the midpoint score of 2.50, which indicates that in general the respondents can be deemed to appreciate the extent to which aspects negatively impact on construction H&S. The top seven ranked MSs are > 3.33 ≤ 4.17, and thus the respondents can be deemed to perceive the extent to be between some extent to a near major extent / near major extent. QMSs complement H&S as they engender quality assurance. Contractor registration complements overall performance and H&S, particularly if H&S is included among the criteria to register. Management commitment and worker participation are the ‘two pillars’ of an H&S programme, and therefore management and worker H&S competencies are important. H&S culture occurs upstream of management system, exposure, and incidents, and therefore a poor or non-existent H&S culture negatively affects H&S. Reference to H&S in standard contract documentation promotes attention to H&S and engenders financial provision. H&S management systems create the framework within which H&S can be managed and they essentially assure healthy and safe work. The aspects ranked seventh to eight have MSs > 2.50 ≤ 3.33 - between a near minor to some extent / some extent. Separation of design and construction marginalises H&S as construction H&S knowledge and expertise is not transferred. Shortened project duration invariably results in the introduction of additional resources into the workplace and often the scope and value of the works being simply incompatible with the available time. H&S needs to be resourced due to the various related interventions and thus needs to be budgeted for - inadequate financial resources are often cited as the reason for not addressing H&S. A related issue is that of competitive tendering, which research has identified as being a barrier to H&S as should a committed contractor make the requisite allowance for H&S they are likely to lose the bid to a less committed contractor. The MS of last ranked H&S pre-qualification falls within the range > 1.67 ≤ 2.50 - between a minor extent to a near minor extent / near minor extent. H&S pre-qualification has shown to positively affect construction H&S.

Table 3. Extent to which various aspects negatively impact on construction H&S.

Aspect	Response (%)							MS	Rank
	Un-sure	Does not	Minor……………………………. Major						
			1	2	3	4	5		
Lack of quality management systems (QMSs)	0.0	0.0	0.0	0.0	7.7	76.9	15.4	4.08	1
Lack of contractor registration	23.1	0.0	0.0	7.7	7.7	38.5	23.1	4.00	2
Lack of management H&S competencies	0.0	0.0	7.7	7.7	7.7	61.5	15.4	3.69	3=
Lack of worker H&S competencies	0.0	0.0	7.7	7.7	7.7	61.5	15.4	3.69	3=
H&S culture	0.0	0.0	0.0	25.0	8.3	41.7	25.0	3.67	5
Inadequate reference to H&S in standard contract documentation	7.7	0.0	7.7	7.7	15.4	46.2	15.4	3.58	6
Lack of H&S management systems (H&SMSs)	0.0	0.0	15.4	7.7	7.7	61.5	7.7	3.38	7
Separation of design and construction	7.7	0.0	15.4	7.7	23.1	38.5	7.7	3.17	8
Shortened project duration	0.0	8.3	16.7	8.3	16.7	25.0	25.0	3.08	9=
Inadequate financial resources	0.0	7.7	15.4	7.7	15.4	38.5	15.4	3.08	9=
Competitive tendering	0.0	0.0	15.4	30.8	23.1	15.4	15.4	2.85	11
Lack of H&S pre-qualification	7.7	0.0	30.8	15.4	30.8	7.7	7.7	2.42	12

Respondents were required to indicate the extent to which their organisations have influenced construction H&S, and the extent to which they could influence construction H&S on a scale of 1 (minor) to 5 (major). The ‘have influenced’ MS is 3.42, and the ‘could influence’ MS is 4.00. Given that the MSs are > 3.33 ≤ 4.17, the respondents can be deemed to perceive the extent to be between some extent to a near major extent / near major extent. These are notable findings in that, firstly, clients recognise the potential to further influence construction H&S. Secondly, the perception on the part of clients that they could influence construction H&S is likely to be attributable to them having influenced it, and the realisation that improvements accrue from contributing to contractors’ H&S.

Table 4 indicates the extent to which improvements have resulted from respondents' organisations' contributions to contractor H&S in terms of percentage responses to a scale of 'No' and 1 (minor) to 5 (major), and a MS ranging between 0.00 and 5.00. All the MSs are above the midpoint score of 2.50, which indicates that in general the respondents can be deemed to perceive that the improvements have been realised. The top two ranked MSs are > 3.33 ≤ 4.17, and thus the respondents can be deemed to perceive the extent to be between some extent to a near major extent / near major extent. The aspects ranked joint third to ninth fall within the range > 2.50 ≤ 3.33 - between a near minor to some extent / some extent. These findings are important as they confirm the benefits to clients of contributing to contractor H&S, which benefits are likely to reinforce clients' focus on H&S and the inclusion of it as a value on projects. Furthermore, the findings confirm the synergy between H&S and the environment, productivity, quality, and time.

Table 4. Extent to which improvements have resulted from respondents' organisations' contributions to contractor H&S.

Improvement	Response (%)							MS	Rank
	Un-sure	No	Minor…………………………….. Major						
			1	2	3	4	5		
Fewer contractor accidents	23.1	0.0	7.7	0.0	23.1	23.1	23.1	3.70	1=
Less impact on the environment	23.1	0.0	15.4	0.0	0.0	38.5	23.1	3.70	1=
Less complications	7.7	7.7	7.7	7.7	30.8	23.1	15.4	3.08	3=
Increased client satisfaction	7.7	7.7	15.4	7.7	7.7	38.5	15.4	3.08	3=
Improved contractor productivity	7.7	0.0	15.4	23.1	23.1	15.4	15.4	2.92	5=
Improved client performance (overall)	7.7	7.7	15.4	7.7	23.1	23.1	15.4	2.92	5=
Improved contractor quality / Less rework	7.7	7.7	15.4	15.4	30.8	7.7	15.4	2.67	7=
Less disruption of client process	7.7	7.7	15.4	15.4	30.8	7.7	15.4	2.67	7=
Improved contractor time (schedule) performance	15.4	7.7	7.7	30.8	23.1	0.0	15.4	2.55	9

Table 5 indicates the extent to which various aspects / interventions can contribute to an improvement in construction H&S in terms of percentage responses to a scale of 1 (minor) to 5 (major), and a MS ranging between 1.00 and 5.00. 15 / 17 (88.2%) MSs are above the midpoint score of 3.00, which indicates that in general the respondents can be deemed to perceive that the aspects / interventions can contribute to an improvement in construction H&S. However, given that the MSs of the aspects / interventions ranked first to twelfth (70.6%) are > 3.40 ≤ 4.20, the extent can be deemed to be between some extent to a near major / near major. The MSs of the aspects / interventions ranked joint thirteenth to seventeenth are > 2.60 ≤ 3.40 - between a near minor extent to some extent / some extent.

It is notable that aspects / interventions related to clients, designers, and contractors, and design, procurement, and construction all achieved MSs above the midpoint score of 3.00. Furthermore, the ranking achieved by H&S, environmental, and quality management systems is notable – H&S (1st); environmental (3rd), and quality (joint 6th). Client related aspects / interventions include H&S, environmental, and quality management systems, and client actions / contributions. Designer related aspects / interventions include constructability reviews by designers, and prioritisation / consideration by designers. Contractor / construction related aspects / interventions include H&S, environmental, and quality management systems, H&S programme, contractor programming, project specific plan for H&S, and project specific plan for quality. Procurement related aspects / interventions include optimum project programme, pre-qualification of contractors on quality, contract documentation, integration of design and construction in terms of H&S, pre-qualification of contractors on H&S, partnering, and choice of procurement system.

Table 5. Extent to which various aspects / interventions can contribute to an improvement in construction H&S.

Aspect / Intervention	Response (%)						MS	Rank
	Un-sure	Minor…………..…………………Major						
		1	2	3	4	5		
H&S Management System (H&SMS)	7.7	0.0	0.0	23.1	38.5	30.8	4.08	1

H&S programme	0.0	0.0	0.0	23.1	53.8	23.1	4.00	2
Environmental Management System (EMS)	7.7	0.0	0.0	30.8	38.5	23.1	3.92	3=
Contractor programming	0.0	0.0	7.7	23.1	38.5	30.8	3.92	3=
Project specific plan for H&S	0.0	0.0	15.4	7.7	53.8	23.1	3.85	5
Pre-qualification of contractors on quality	0.0	7.7	0.0	30.8	30.8	30.8	3.77	6=
Optimum project programme	0.0	7.7	0.0	23.1	46.2	23.1	3.77	6=
Client actions / contributions	0.0	7.7	0.0	30.8	30.8	30.8	3.77	6=
Quality Management System (QMS)	0.0	0.0	7.7	30.8	38.5	23.1	3.77	6=
Contract documentation	0.0	0.0	7.7	30.8	46.2	15.4	3.69	10=
Project specific plan for quality	0.0	0.0	15.4	23.1	38.5	23.1	3.69	10=
Integration of design and construction in terms of H&S	0.0	7.7	7.7	30.8	38.5	15.4	3.46	12
Constructability reviews by designers	0.0	0.0	15.4	38.5	38.5	7.7	3.38	13=
Pre-qualification of contractors on H&S	0.0	15.4	7.7	23.1	30.8	23.1	3.38	13=
Prioritisation / consideration by designers	0.0	7.7	0.0	61.5	15.4	15.4	3.31	15
Partnering	7.7	23.1	7.7	30.8	23.1	7.7	2.83	16
Choice of procurement system	7.7	30.8	0.0	30.8	30.8	0.0	2.67	17

4. Conclusions

The traditional project parameters of time, quality, and cost are more important than public H&S and project H&S. Given that public H&S is more important than project H&S, it can be concluded that clients are more concerned with the public than the workforce. This conclusion is reinforced by the importance afforded construction ergonomics.

Given that the respondents' organisations can be deemed to have influenced and contributed to contractors' H&S relative to a range of interventions / requirements, it can be concluded that clients do influence contractor H&S. They do so directly through requiring contractors to participate in their H&S activities, or compliance with their systems, and procedures, and indirectly through interventions that create an enabling environment.

Clients identified the role of a range of aspects in terms of their impact on H&S. Therefore, it can be concluded that clients understand and appreciate the role of design, procurement, H&S culture, management, H&S training, and resources, in H&S performance. This bodes well as such an understanding and appreciation is likely to reinforce their involvement in and contributions to contractor H&S, and possibly stimulate either intensification of or further involvement and contributions, or both.

Client organisations contend that they have influenced construction H&S, and that they could influence construction H&S more. Therefore, it can be concluded that clients do influence construction H&S. Furthermore, the recognition that they could influence construction H&S more, is also likely to reinforce their involvement, and possibly stimulate either intensification, or further involvement, or both.

Clients identified that a range of benefits accrue from their contributions to contractor H&S. Therefore, it can be concluded H&S plays a holistic role in project performance. Furthermore, from an investment perspective, clients have realised a return on their investment in contractor H&S. This in turn is also likely to reinforce their involvement, and possibly stimulate either intensification or further involvement, or both.

Clients identified that a range of design, procurement and construction aspects / interventions can contribute to an improvement in construction H&S. Therefore, it can be concluded that H&S performance can be improved, and that all stakeholders can contribute to such an improvement.

5. Recommendations

H&S should be included as a value on all projects, and afforded status at least equal to that afforded to cost, quality, and time. This can be achieved by the following primary interventions on all projects: the inclusion of H&S during decision making all levels and during all reviews; project specific H&S requirements; H&S goals; the facilitating of optimum financial provision for H&S; the inclusion of H&S as a criterion for pre-qualification; the appointment of H&S conscious project managers, designers, quantity surveyors, and contractors; the inclusion of H&S as an agenda item for all meetings; project H&S reporting in the form of 'leading' and 'lagging' indicators, and requiring of a project close out report which includes H&S.

In addition, clients should create an enabling environment through the following: the implementation of an H&S management system within which contractors and their supply chain can be managed; the selection of appropriate procurement systems, and the identification of optimum project durations.

Furthermore, clients should undertake direct and indirect interventions relative to contractor H&S. Client provided H&S induction and training constitutes direct interventions. Conducting constructability reviews and requiring contractor employee identification constitutes indirect interventions.

The SAPOA and professional associations should contribute to the realisation of optimum status being afforded to H&S upon the revision of standard industry contract documentation. Public sector clients should include H&S as a criterion when assessing tenders.

Tertiary education property related programmes should address construction H&S and ergonomics, and SAPOA should evolve construction H&S, and ergonomics practice notes. However, this should not be constrained to the property sector, but expanded to include construction project manager, designer, and quantity surveying tertiary education programmes, accompanied by interventions from the related professional associations. The role of all stakeholders should be addressed by all the respective disciplines.

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Dealing with Ageing Workforce in the Hong Kong Construction Industry: an Initial Exploration

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Abstract

The workforce in the 21st century is ageing. There is increasingly larger proportion of workforce 50 years of age or older. This ageing situation is prevalent in the Hong Kong construction industry as about 41% of total registered construction workers in Hong Kong are 50-year-old or above as at 31 Aug 2018, and the failure of the industry to attract younger workers. These situations have collectively led to serious manpower shortage. Most construction workers are experiencing physically demanding works on a daily basis. Workers are also subjected to constant psychosocial pressures including the need to face stressful environmental conditions, long and sometimes irregular work hours, unpredictable workplaces and conditions, and dis-continual employment. In addition, the organisational and institutional arrangements in Hong Kong construction industry are less supportive in providing favourable working environment for older workers. Despite these misgivings, we know very little of the conditions older construction workers experience in Hong Kong construction industry. There is therefore a need to investigate such issues and propose possible intervention to improve the working conditions of our senior workers. With these objectives, in this paper, we first report the findings of a small scale survey on the care of older workers in Hong Kong construction industry, and second propose potential intervention by combining the findings of the survey and our industry observations of the practices implemented by progressive contracting companies in Hong Kong. In developing the intervention scheme, we draw from the approach of the emerging field of integrated health and safety protection and promotion. The scheme focuses on the relationships and causal pathways of the conditions of works to workers' health and safety outcomes by taking into consideration the organisation and workforce characteristics. It is argued that the framework can potentially mitigate the risks associated with ageing workforce.

Keywords: Ageing workforce; construction workers health safety and well-being; integrated approach; protection and promotion; working conditions

1. Introduction

The workforce in the 21st century is ageing. There is increasingly larger proportion of workforce 50 years of age or older. A few societal and demographic trends have led to this development [1] including general population ageing, increase life expectancy, and decline in fertility rates [2,1]. Hong Kong is not immune from these trends. These trends affect the composition and the supply of workforce. The most obvious result of these situations is the large increase of older workers. This situation brings about implication on workforce productivity and by extension, the economic prosperity of business enterprises. As physical and cognitive functions decline with age [3], the older workers'

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productivity suffers and susceptibility to ill-health and safety issues increase. To remain competitive or to simply keep the business in operation, employers face the challenging tasks of having to maximise the contributions of both the old and young workers while at the same time addressing the health, safety, and well-being issues of the workforce [1]. These ageing situations are prevalent in the Hong Kong construction industry considering the fact that about 41% of the total registered construction workers in Hong Kong are 50-year-old or above (as at 31 Aug 2018 [4]), and the failure of the industry to attract younger workers, which have together led to serious manpower shortage [5,6,7].

As with most countries and regions, construction workers in Hong Kong experience physically demanding works on a daily basis. Workers are also subjected to constant psychosocial pressures including the need to face stressful environmental conditions, long and sometimes irregular work hours, unpredictable workplaces and conditions, and dis-continual employment [8]. In addition, the organisational and institutional arrangements in Hong Kong construction industry are less supportive in providing favourable working environment for older workers [9]. These conditions have collectively taken a toll on the safety, health, and well-being of construction workforce in general and older workers in particular. Despite these misgivings, we know very little of the conditions older construction workers experience in Hong Kong construction industry. There is therefore a need to investigate such issues and propose possible intervention to improve the working conditions of our senior workers. For these purposes, in this paper, we first report the findings of a small scale survey on the care of older workers in Hong Kong construction industry and second, propose potential intervention by combining the findings of the survey and our industry observations of the practices implemented by progressive contracting companies in Hong Kong.

1.1. Hong Kong construction general workforce health, safety, and well-being

Some works and research studies conducted in the past several years in Hong Kong construction industry have led to the revelation of insights on the general workforce health, safety, and well-being although these studies were not solely targeted at older workers. Notable among these studies were the four waves of health promotion and medical examination exercises conducted during the years 2013 to 2018 by staff members of two local universities – Rowlinson et al. [10], Tin et al. [7], Yi and Chan [11], and the currently ongoing Chan's [12] construction workers' health profiling project. The results [except Chan [12] the results of which are pending] of these studies converge to indicate that the local workforce sustain poor health conditions. There is a high prevalence of hypertension (22.6%), overweight (71.7%), undesirably low level high-density lipoprotein (HDL) (41.6%), and diabetic levels of non-fasting blood glucose (4.3%) among the workforce, and 48.7% of the workforce are involved in high risk smoking [7]. In terms of well-being, Rowlinson et al. [10] report that with the long work hours (80.9% of the workers sampled work more than 9 hours a day, 6 days a week), the work-interference with family is more likely than family-interference with work. These long work hours lead to fatigue, less satisfaction in work-life balance, and compromised safety performance.

In addition to these studies, the findings of a small-scale single-organisation construction workforce health survey collaborate the above observations. A large contracting firm - a main contractor - in Hong Kong had conducted a general health survey for both their own labourers and sub-contractors workers in 2017. The number of workers surveyed was around 3,400. The findings indicate that among all the workers that sustained abnormal blood pressure, around 60% of the workers aged 51 or above; for workers with abnormal blood sugar level, over 55% aged 51 or above; and for abnormal total cholesterol, the percentage was 40% [13]. Taken together, these studies indicate that the construction workforce is sustaining compromised physical health that might lead to significant social and economic consequences [7]. In this workforce, workers 50 years of age or order sustain an acutely impaired health conditions.

1.2. Integrated health and safety protection and promotion for construction workforce

We have learnt of construction workers' (ill)health conditions from preceding paragraph. Because improving the health status, workability, limitations, and barriers in employment arrangements of older workers is important for the workplace health and safety and critical for (older) workers, their families, employers, and the industry at large, there is a need to investigate potential interventions that can be implemented to mitigate the risks associated with ageing workforce. The development of a more holistic approach to improve (older) worker health protection and promotion is needed. In this approach, two factors – worker's personal health and personal safety – are combined to increase the impact on worker's overall health and productivity. The underlying rationale is that when health protection and promotion are integrated and deployed in a systemic manner, the workforce would become healthier and safer. Hymel et al. [14, p.695] has described workplace health protection and promotion as "the strategic and systematic integration of distinct environmental, health, and safety policies and programmes into a continuum of activities that enhances the overall health and well-being of the workforce and prevents work-related injuries and illnesses." The approach involves essential elements that prioritise a hazard-reduced work environment and recognises the role of job-related factors that affect workers' health and well-being [15]. There is an emphasis on the importance of improvements in working conditions that assess and address stressors in the workplace. The approach encompasses workforce participation, job demands, control, worker support, relationships, roles, and organisational change [16].

Sorensen et al. [17] have proposed a conceptual model for the integration of workplace health protection and promotion. The model is shown in Fig. 1. The model specifies the causal pathways upstream phenomena influence downstream worker safety and health and is built on the premise that improvements in safety and health outcomes can only be achieved through addressing multiple pathways in an integrated manner. "Conditions of work" is placed in the centre of the model as factors determining the safety and health outcomes of workers and as mediators affecting the safety and health behaviours of the workers. But at the same time, conditions of work are also affected by upstream organisational and workers characteristics, and organisational policies, programmes, and practices. In addition, although not shown in the figure, the model operates within the context of labour market, economic, legal, and political forces and social norms and influences. It is in this systemic manner that the concept contributes to the organisational and individual outcomes. The model highlights the complex interplay of individual workers and their immediate work environment which are collectively embedded in the larger context that affects the outcomes of the workers (e.g., health and safety behaviours) and where improvements are likely to be made [17].

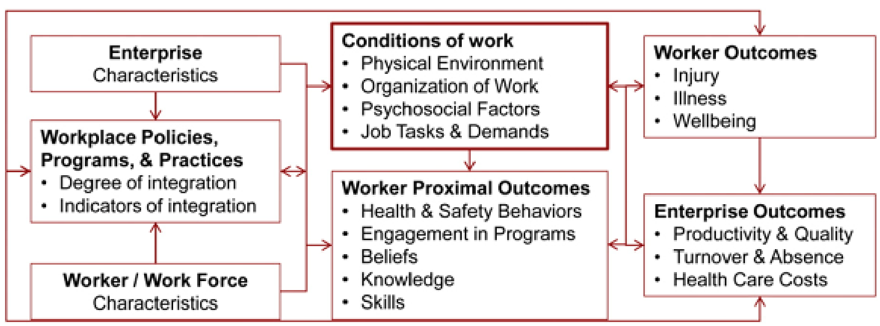

Fig. 1. Sorensen et al.'s [17] integrated model of workplace health protection and promotion.

2. The small scale survey on older workers care

The third author of the paper had conducted a small scale survey in December 2017 to investigate the situations on the care of older workers in Hong Kong construction industry. The survey was conducted within a client-based benchmarking group in Hong Kong and aimed to explore the arrangements that had been (or had not been) put in place for the care of older workers in the industry. Thirty-nine main contractors and two client organisations participated in the survey. The survey investigated the extent of measures implemented by these organisations for the care of older construction workers. These measures include the implementation of (a) specific written policy for the care of older workers, (b) age definition of older worker, (c) health check arrangements, (d) specific site arrangements for elderly workers, and (e) promotional activities.

The 39 main contractors were classified as large-size contractor in Hong Kong. These contractors are capable of handling contract values that exceed HK$300 million (Euro1: HK$9 as at April 2019). Middle to senior personnel of these organisations responded to the survey including project director, project manager, site agent, project engineer,

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general manager, etc. The findings of the survey is presented in Fig. 2. In the figure, the sequence of the charts corresponds to the measures being investigated in the survey and the number in the chart represents the number of respondents (i.e. organisations) that implement the measures being asked.

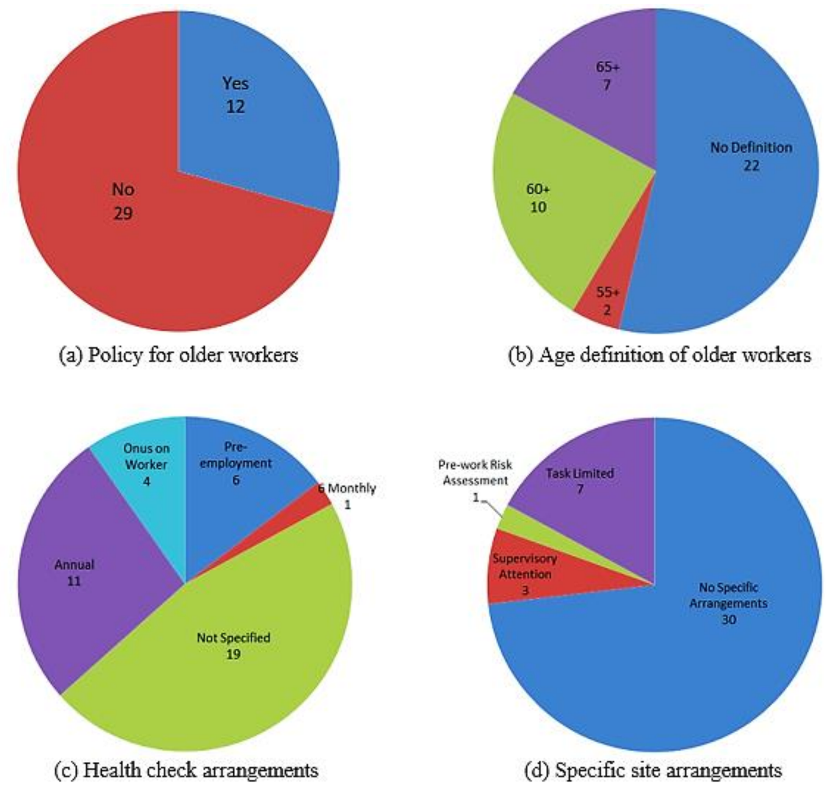

Fig. 2. Findings of the survey on older workers care.

In Fig. 2, as shown in chart (a), 29 respondents (71%) indicated that no specific written policy was put in place for the care of older workers whereas 12 respondents (29%) had determined specific age defining arrangements. This observation has led to the finding in chart (b) whereby the overall majority of respondents indicated that there was no age categorisation for older workers and a ten year variation is noted with other organisations who indeed define “older workers” with the age ranges from “55 and above” to “65 and above”. For health check arrangements, as presented in chart (c), there is a wide variation on arrangements being adopted. Of particular note is 1 contractor who provides six-monthly hypertension and blood pressure tests for those over sixty years of age. At the other end of the “care” scale 4 respondents placed responsibility on older workers to provide proof of fitness to work on sites. And finally in chart (d) where greatest consistency is shown in that, in most cases, no specific arrangements apply at site related to the care of older workers. Majority of those surveyed (30 organisations, 73%) responded in this way.

As for question (e), a range of health-related promotional activities were reported in the survey. Several respondents – 9 organisations – placed importance on educational briefing related to healthy lifestyle issues (e.g., diet modification); 3 respondents placed importance on blood pressure / vascular screening and had measures in place to escalate “care” if negative results were noted; 1 respondent was in the process of setting up a specific site medical centre; 1 respondent mentioned of the duty of the site nurse to look out for the welfare of older workers; and 1 respondent mentioned morning exercise as a control related to older workers.

In addition to the survey, anecdotal evidence from our observation of the construction industry in Hong Kong reveals that a myriad of health measures have been implemented by several more progressive contractors. These measures range from basic regular health checks, personalised health advice, lifestyle review, medical counselling; to the integrated health diagnostics, centralised health record, analyses, and company-wide health and work design (cf. [13]).

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Although these health measures are put in place for the benefits of workers of all ages, older workers may benefit more as they are the group with higher proportion of the workforce that sustains impaired health conditions than their younger counterparts.

3. Discussion

The findings point to a general situation of under-appreciation of the ageing workforce issues in the Hong Kong construction industry. This general lack of appreciation and understanding are manifested in the findings that majority of the main contractors have not specified the age limit for workers to be considered "older" and consequently have not implemented specific work practices and site arrangements for this group of workforce. For a few contractors that specified the age limit (from 55- to 65-year-old) and those that have put in place some arrangements – additional supervisory attention, pre-work risk assessment in relation to workers' capacity, and age-based task limitation – there appears to be a need to re-examine the attitudes and assumptions of contractors with regard to the suitability of the older workers for construction operations. In terms of attitude, traditionally, contractors are concerned with additional financial cost in implementing specific work and organisational arrangements to cater for the older workforce and this is within the broader context of construction workforce employment arrangement, client responsibilities, and workers' pay structures [9] and that, contractors will be unable to recoup the financial outlay in a competitive industry [18]. However, along with this seemingly backward attitude, at play is also a situation of the understanding of works that is based on a set of uninformed assumptions, the assumption that older workers are associated with reduced productivity and that, they are more susceptible to health and safety problems. Despite this attitude, employers are still expected to ensure that workers are physically able to perform their works in safe and effective manner. In this respect, it is possible for employers to implement interventions that minimise biological and physical ageing by matching the task to the capability of workers. For construction operations, assigning physically demanding tasks to capable younger workers [3] would benefit a group of workers as the capacity of the older workers to tolerate peak loads decreases with age. Along this arrangement, it is also possible to introduce flexibility to modulate work intensity by encouraging work group self-regulation [c.f. 19]. And as usual, the introduction of ergonomically friendly work environment can reduce the risk of injury in older workers [1]. It is hence possible to maintain older workers' capacity or even get more out of the workforce by modifying existing practices and work conditions without incurring huge financial outlay.

In fact, the focus of construction firms should be to modify the work environment to reduce physical demands, providing alternative work arrangements, and facilitate improvements in workers physical capacity [19, 20]. These notions essentially call for a combined health and work conditions intervention. Our industry observations of a few progressive contractors in Hong Kong has revealed of the implementation of an integrated health protection and promotion model as shown in Fig. 3. The measures in the model include improvements of work environment (e.g., providing age-friendly work tools) and work arrangements (e.g., additional risk assessments based on role and capability in relation to workers age, additional health surveillance). As workers age, chronic diseases and functional impairment limit the ability for them to work. Mental health problems (e.g., depression and anxiety) have also been reported as common causes of work disability [21]. As shown in the model, the combination of the measures essentially introduces a preventive approach that is not only beneficial for workers of all ages but is potentially effective in mitigating the risks associated with ageing workforce in construction.

The model in Fig. 3 shows that company policies influence worker health and safety outcome through a few pathways. These influences are mainly mediated through the "Conditions of Work". Company's policies directly affect physical work environment through for example safety and health practices. These practices impact physical demands on older workers in relation to biomechanical sources of strain [17]. The work environment may also support healthy behaviours among workers for example through exercise (see "Leisure physical activity" under Worker Proximal Outcomes). Organisation of work, with the listed activities, will influence worker health and safety outcomes. For example, the implementation of heat stroke prevention measures is likely to reduce the workforce heat stress / stroke incidents. Psychosocial factors deal with job strain, psychological demands, social support, and peer influence. In this regard, initiatives of workplace stress management and rapport building that support health and safety behaviours are likely to lead to improved health behavours [22]. In addition, positive workplace psychosocial conditions also reduce the risk of musculoskeletal disorder (MSD) [23]. Essentially, the model and its component measures propagate of a transformational change in the organisation toward a culture of workplace safety and health that are supportive of workers total well-being.

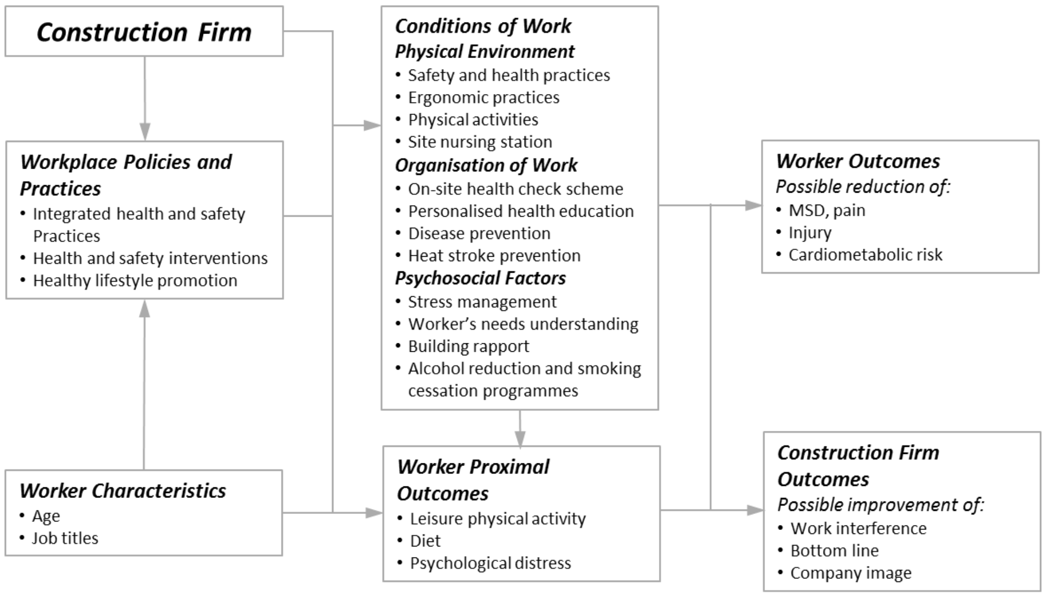

Fig. 3. The application of integrated model of workplace health protection and promotion in construction firms [adapted from 13 and 17].

4. Conclusion

In this paper, we set out to explore the care measures for older workers and potential interventions implemented by some progressive contractors in Hong Kong. Given the economic pressures of keeping older workers in the construction working population and the need to understand the role of age in the development of disease and the impact on occupational injury and safety, our exploration has shed some lights on the attitude of the contracting community in treating older construction workforce which at best can be described as lukewarm (and at worst ignorantly minimalist and shortsighted). But at the same time, our industry observation of a few progressive contractors has revealed of a range of interventions that are in line with the emerging concept of worker health (and safety) protection and promotion – an integrated scheme for workplace safety, health, and well-being – that can potentially bring about positive change in the industry. As shown in Fig. 3, the implementation of such an integrated scheme can help companies to understand the relationships between working conditions and workers safety and health outcomes. This in turn informs the company on priority setting and more importantly, identify the impact of health and safety on business related outcome. The implementation of such an integrated scheme of workplace health and safety protection and promotion appears to hold promise in the management of ageing workforce. The implementation of such good practices, if done correctly and consistently across the construction industry, will bring the industry forward in terms of its management practices and its reputation. Such good practices will help to ensure that our workplaces are able to meet the senior workers' needs and capacities.

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Digital construction and its role in driving the circular economy

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Abstract

Digital technologies can be used at any stage of the life cycle of a construction project, from the concept of the facility to the final of its operation. Construction companies use more and more available technological solutions, increasing mobility and safety at the construction site and facilitating the construction process. Digitization is increasingly affecting the modernization of the building management and operation process, saving time, making decision-making easier, causing saving financial resources and reducing the costs of energy and materials consumption. Not only investment of construction entrepreneurs in internal start-ups has been observed, but also the reverse phenomenon, involving the interest of technology companies in the construction investment market.
The closed-circle economy allows economic growth while reducing and optimizing resource consumption - it deeply transforms patterns of production and consumption chains and designs business models anew. The aim of the article is to present the results of the literature review, from the angle of discussion of issues related to the digital technologies used in various stages of the life cycle of construction projects with the assumptions of a closed-cycle economy. three successive steps were carried out: (1) a search strategy was developed to systematically review the literature and collect a representative set of publications on the relation of circular economy to building and digital technologies applicable to the life cycle of a building facility using Google Scholar; (2) a list of publications in the ad-doc database was prepared in order to synthesize the literature review; (3) a subset of the literature reviews was organized, which enabled the acquisition of quantitative and qualitative data as well as information on the phenomenon of digital construction and the impact of this innovative change on the development of the concept of closed circuit economics.

Keywords: digitization; BIM; construction sector; circular economy

1. Introduction

The traditional linear production model (linear economy) assumes a schematic course of the production process in which the following stages are successively followed: obtaining raw materials, processing and then disposing of the product (take, make, dispose).

According to the circular economy paradigm, the materials and articles used in production are designed to be re-usable or safely introduced into the biosphere, and the technologies used in production cycles are environmentally safe [1,2,3,4]. This is an extension of the "cradle to cradle" production idea, which was defined for the first time by Stahel [5]. In this manner, the production model is changed and now includes stages: “take-make-consume-reuse and recycle” [6,7]. In the macroeconomic context, in relation to the functioning of regions, especially urban areas, the

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concept of circular economy refers to other complementary economic solutions, e.g., to the concept of sharing economy, according to which, unlimited consumption or accumulation of property gives way to their common use, exchange or borrowing of possessed goods [8]. One of the key issues in business models based on the economics of closed-loop (CE) is that instead of selling and buying products, they are manufactured with sustainability and then, where possible, they are leased, rented or shared [9]. An important feature of the concept of closed-loop economy is the fact that it allows for the elimination of conflict between the issues of economic profitability and ecological effectiveness of the business activity.

2. Method

The results presented in the article were obtained using the method of systematic literature review defined as the 5-stage review approach. This method is appropriate in the case of explanatory research concerning complex phenomena, which, in the authors' opinion, include the integration of CE assumptions with the digitalisation trend in the construction industry. Fig. 1 illustrates the course of the test in a schematic manner.

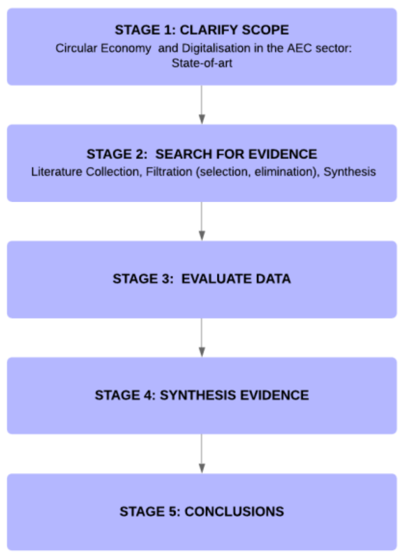

Figure 1. The 5-stage review

As a first step, a study area was identified and its aim was to establish, as a result of a literature review, the current state of knowledge related to the potential of digital tools used in construction in relation to the implementation of Circular Economy in this sector and Digitalisation in the AEC sector: State-of-the-art. The second step included Literature Collection, followed by Literature Filtration and Synthesis. Publications were searched for using the Google Scholar database and the Web of Science. A timeframe was adopted from 2000 to 2019. The search was carried out using these keywords: 1. digital construction + circular economy 2. BIM + circular economy, 3. Digital tools + LCA in construction projects. From among 95 articles, and as a result of a preliminary analysis of their content 65 were chosen, which, in the author's opinion, presented the most adequate relationship with the subject of the study. The next steps concerned a detailed and critical analysis of selected articles, which resulted in the identification of the main thematic areas of the links between digitisation and CE in construction, the determination of the current state of knowledge on the subject and the identification of areas that require further knowledge and research.

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3. Circular economy in construction – main assumptions

The implementation of circular economy in the AEC sector is particularly justified due to the very intensive and degrading impact of this sector on the natural environment and on a single building scale, as well as on a regional and global scale [10]. Architecture and construction in line with the circular economy aim to reduce the use of natural resources, reduce the amount of waste and reduce the impact of buildings on the environment. In terms of architectural practice, methods have been developed in recent decades to accurately predict the reuse of recovered materials outside the "end-of-pipe" design solutions that only delay the waste phase [11]. In buildings designed in accordance with the principles of closed-loop management, secondary materials are used, but above all, facilities are designed in such a way that their elements can be recovered in the future. Life cycle analysis of a building's structure allows for the identification of key aspects of circular economy in subsequent stages of this cycle (Fig. 2) [12].

Figure 2. Key aspects of circular economy in subsequent stages of the building life cycle. Based on [12].

The general principles of circular buildings can be summarised as follows:

- it has been proposed to minimise the total energy expenditure on the maintenance of the building and to move towards net zero energy buildings, i.e. those in which the used energy comes entirely from renewable sources,

- circular buildings, apart from energy conditions, are materially conditioned. Construction products should have well-defined technical characteristics, well-defined usefulness and be well suited to the application in question. Technical features not used in a given application or representing excess values constitute an unreasonable cost (energy input) which is paid for by the user.

The 3R - Reduce-Reuse-Recycle concept, according to which unused structural elements or other construction waste is used, adapting projects to limit construction activities to the minimum necessary, is well known in construction activities [13,14]. Circular economy extends this approach by prioritising the deconstruction of facilities before demolition and recycling of demolition materials [15].

Analysing the circular buildings framework model, two issues important for further consideration are identified. The first concerns the specificity of construction production, which is much more complex than in the case of the industrial products with short life cycles. This means that the solutions proposed under the CE concept for industrial production are not fully adequate for the AEC sector. At the same time, construction facilities are constructed from elements, materials and products which separately constitute products with characteristics similar to industrial products (manufactured products), while being integrated into the structure, they acquire common features of uniqueness, durability and long life cycle, far removed in time from the creation of the transformation possibility [16].

The impact of the implementation of circular economy principles on ecological efficiency and, at the same time, the profitability of production, can be observed on the example of the results of research conducted from the perspective of the supply chain, comparing the results of LCA analysis for two insulation materials, one of which is produced in the traditional linear method, the other with the use of the closed-loop method. According to the obtained results, a smaller impact can be observed with regard to the second material, produced according to the assumptions of circular economy [17].

Publications indicate that technology is a key aspect in construction, enabling the creation of circular loops, combining supply and demand, as well as the handling, storage and management of the vast amount of data required by CE.

In the case of construction facilities, the range of data over the whole life cycle of such a facility is very large and varied. Relevant data in addition to facility information resulting from the construction project include schedules, cost information, energy analysis details, lighting information, waste management plan, etc. This additional data is used at different stages of the facility's life cycle for various analytical, simulation and evaluation purposes.

Due to the need to manage resources and information wisely throughout the life cycle of a building, the possibility of using digital technologies that can support the implementation of CE in the AEC sector has become increasingly important in recent decades [16].

3.1. Digitisation of the life cycle of a building - enabler of CE in the AEC sector

The effectiveness of a business model implemented according to circular economy assumptions can be supported by digital technologies, which facilitate and help to close or slow down material flows, with increased resource efficiency [17,18,19,20,21].

Literature, which discusses the opportunities and challenges of the impact of digitisation on the results of the implementation of CE in construction processes is relatively limited. As a result of the analysis of selected publications, thematic mainstreams combining the issue of CE and digital technologies in the AEC sector, in terms of the life cycle of the building, have been identified (Fig. 3).

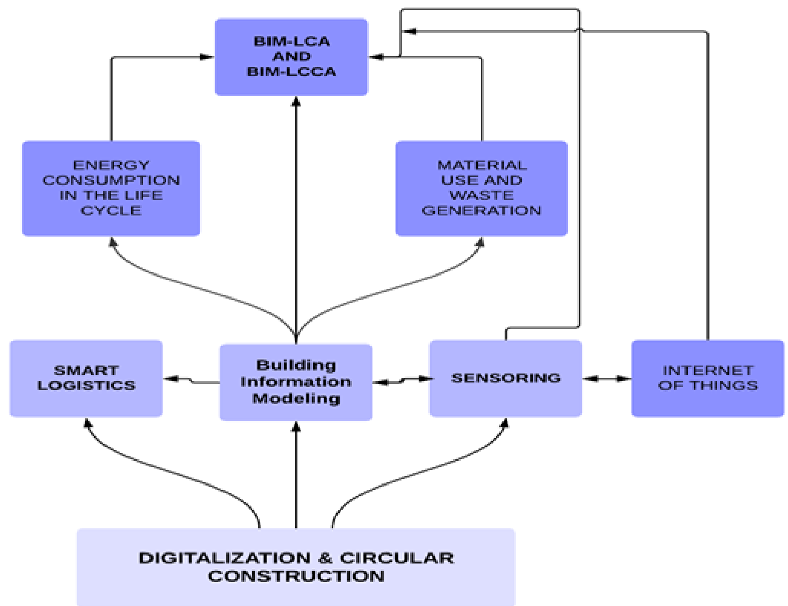

Figure 3. Thematic mainstreams combining the issue of CE and digital technologies in the AEC sector

The results concerning the issue of BIM and circular construction are presented in tabular form (tab.1).

Tab.1. Articles concerning the linkage between the issue of BIM and circular construction

Thematic trend linking CE and BIM	**Publications**
Building Information Modelling (BIM)	
and Energy	[32], [40], [41], [42], [44], [55]
and Material consumption (waste utilization)	[27], [29], [34], [39], [47]
LCA	[23], [24], [25], [26], [28], [30], [31], [33], [35], [36], [38], [43], [45], [46], [48], [49], [50], [51], [52], [53], [54], [56], [57], [58], [59], [60]
LCCA	[61], [62], [63], [64]

The results of the literature review related to the possibilities of implementing the BIM method in the context of achieving sustainable development goals in the construction industry show that there is a significant amount of research and development in this use of BIM at different stages of the project. One of the key features of BIM, which makes it a suitable method for use in the life cycle of a building in accordance with CE assumptions, is the ability BIM offers three basic functions that make it both an economically and environmentally efficient way to manage the life cycle of buildings. These basic features include: (i) parametric modelling of objects, (ii) bidirectional association and (iii) intelligent modelling [26].

Publications of solutions integrating BIM tools with sustainability analysis applications indicate two main approaches. The first one concerns the combination of environmental analysis instruments already developed and functioning in practice with BIM tools. The second approach proposes the development of new analytical tools with the ability to communicate with BIM software. The choice between these solutions determines the costs of modification of already used programs and implementation of new tools [34].

The thematic scope of a significant part of publications related to BIM synergy and sustainable construction principles, concerns material analysis of building structural elements. This is based on the premise that, in order to ensure the efficiency of circular economy in construction, it is important that a significant proportion of the construction materials and used products should be reusable and recyclable [33,35]. Tools related to this area include Materials Passports and Reversible Building Design Protocols (RBDP). The first instrument contains digital sets of data describing defined characteristics of materials and components in products and systems that give them value for present use, recovery and reuse. RBDP contains a set of instruments to inform designers and decision makers about the technical and spatial reversibility of building design(s) and the impacts of design solutions during the conceptual design phase.[36].

However, only a few works can be identified concerning the possibilities offered by the BIM method for increasing the ecological efficiency of the renovation and demolition of the building. [37, 38].

The use of BIM has also been analysed in the context of the zero-carbon buildings concept. [39,40,41,42]. Achieving zero carbon emissions in buildings requires monitoring and sharing information and knowledge about building performance during operation, from the moment the building is handed over to the occupants. One of the main assumptions of the BIM method is the discipline of cooperation between all participants of the investment process, which significantly facilitates the exchange of information and knowledge between the interested parties. The concept of BEM - Building Energy Modelling is related to the issue of energy efficiency. In the Building Energy Model, it is possible to study the impact on the energy efficiency of different design variants (e.g., different thicknesses of thermal insulation in a building), to test different variants of installation and automation. The building model is located in a specific geographical location for which a set of meteorological data is used. As a standard, calculations for simulations are performed with a frequency for each hour of the year (8760 hours), which gives great accuracy of results, incomparable with, for example, the results obtained from the preparation of the energy performance certificate of the building [43].

The integration of BIM with analytical tools related to sustainable construction concerns analyses in the area of ecological footprint and LCA. LCA analysis makes it possible to assess the environmental impact of a building facility by estimating the raw materials and energy consumed at different stages of its life cycle, as well as the amount of pollutants emitted.

It is a tool used to quantify environmental loads generated during the manufacture of construction products and the erection of buildings. LCA has great potential to support sustainable construction. However, in a traditional construction process, due to the limited data availability and time-consuming process of compiling this data, LCA analysis is not widely used. The BIM method, which uses a model that provides a comprehensive repository of knowledge about the object, creates perspectives for improving the LCA procedure. Restrictions are pointed out and are mainly related to the interoperability of BIM and LCA tools, but the authors describe significant opportunities to increase the speed of LCA calculations using a repository that collects building data in one place, which covers a very wide range [44]. Researchers also propose an automatic LCA calculation model at an early stage when developing the first data level in the BIM model (LOD100), and then expanding and updating the calculations as the object model develops. This method requires checking the application possibilities with the use of available IT tools [45]. In reference to the assumptions of circular economy, the area which requires deeper knowledge and research work towards the development of new tools is the integration of BIM and LCCA [46 – 60]. At the design stage, it is possible to determine about 80-90% of the costs incurred subsequently over the course of construction, use and operation of the facility, hence it is an adequate stage of the life cycle of the facility in terms of optimising these costs. [61, 62]. The integration of the BIM model and analytical tools used in LCCA is a direction of development of instruments that can significantly improve cost optimisation due to the possibility of faster and more accurate examination of operating scenarios of the facility and determination of costs in accordance with the assumptions of circular economy, especially in terms of its operation and demolition [63,64,65]. This is one of the most important trends in the development of construction on a global scale [66]. One of the concepts concerning tool solutions is Computer Aided Life Cycle Cost Analysis (CA-LCCA) of a building both for new projects and renovation jobs. This tool allows for the combination of technical parameters and financial data to help make investment decisions [67]. Another proposed solution analysed within the case study is the integration of data collected in the BIM, BEM and BIM-FM into LCCA tools. The results indicate a significant increase in the accuracy of calculations and an acceleration of the cost data analysis process [68].

Sensoring enables the collection and generation of data in real time. Current, detailed information on the exact location of waste production, its exact material composition, etc. can be recorded ("fast data") and forwarded to other companies, who then use it as secondary material to plan their production processes. Big Data applications can then provide and design information for further use as practical logistics solutions.

Such solutions are increasingly used in office buildings and large service buildings like shopping malls. Systems using sensors and the Internet of Things (IoT) record, monitor and constantly report data from the current use of the building, which allows for the creation of a profile of historical and real-time behaviour, which is useful in FM. When complex data from several assets are aggregated, emerging patterns of usage, energy consumption, preferred lightening and temperature, and collections of interior assets can lead to reconfigured workforce patterns and reduced energy consumption [69].

The idea of "smart contracts" is related to the issue of sensoring – digital contracts functioning in the form of self-service applications. A sensor-equipped intelligent building component can send information about its performance to a distributed data base. Components can be programmed via "smart contract" to initiate the necessary maintenance or repair work, which prevents deterioration of the building and optimises maintenance costs, providing predictive just-in-time maintenance versus just-in-case costly maintenance. The results of the life cycle analysis of individual objects can be compared, on the basis of which it is possible to work out a data set on standard user habits, energy and water consumption, maintenance mode, for the purpose of Facility Management improvement [70].

Adapting supply and demand to the availability of waste or secondary raw materials can be revolutionised through the use of online solutions, as is already the case for product distribution. A potential automated market and logistics platform have the capability to reduce search and transaction costs. This could also facilitate economy of scale, as the question of the amount of materials needed would be more transparent [71-74].

4. Conclusions

The idea of circular economy is derived from concepts that have been in development since the 1970s, especially since the great energy crisis in 1973. These included concepts such as Cradle to Cradle, Regenerative design, Biomimic and Blue economy, initiated by Belgian businessman Gunter Pauli. The effectiveness of the implementation of circular economy in the AEC sector can be increased by combining the digitisation trend with the use of tools related to environmental and economic analyses at every stage of the life cycle of a building.

An area which, according to the findings of the literature review, requires in-depth research is the integration of economic aspects with environmental analyses with the use of digital tools. The issue of inclusion of costs related to life cycle analysis results is the subject of a very limited number of publications. Meanwhile, it is an issue that fills the scope of implementation of the circular economy in the construction industry, due to the inclusion of the financial aspect in the analyses. Until now, the calculation procedure for LCCA analysis required time-consuming data collection for the purpose of determining the costs of procurement of raw materials, transport to the production site, costs of production of construction materials and products, transport to the construction plan, cost of impact at the construction stage, then environmental costs of loads associated with the operation of the building and, finally, its decomposition, including the costs of recycling demolition waste. The calculation process itself, depending on the chosen method, can also be complex, especially if the calculation method assumes an analysis of the discounted cash flows over the period from the construction work up to decommissioning, taking into account different cost elements over the life cycle (e.g., maintenance, use, repairs, overhauls, dismantling). The use of digital tools such as the BIM model in combination with LCCA principles can help optimise investment decisions. In order to broaden knowledge in this area, it is justifiable to check the application possibilities of the proposed model LCCA and BIM solutions, using the case study method. This may be an interesting direction of research, useful both for private investors and institutions implementing public investments, which should be planned in a way that ensures rational use of public money and in a manner consistent with the assumptions of sustainable development and circular economy.

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Do Thermal Comfort Standards Ensure Occupant Satisfaction? Learning From Occupants' Thermal Complaints

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Abstract

Today, buildings are operated according to the standards (i.e. thermal), however; the recommended values in the standards might not necessarily address occupants' needs, and, thus, occupant complaints might arise. This study aims at assessing the performance of the predicted mean vote (PMV) model to detect occupant thermal dissatisfaction. The case study was conducted in a commercial building located in Paris, France between January 2017 and May 2018. Indoor environmental conditions were monitored via sensors and an online tool was used to collect occupant thermal complaints. A total of 53 thermal complaints were analyzed and the corresponding measurements were checked against the reference values suggested by the ISO 7730 Thermal Comfort Standard. The results show that all of the operative temperature measurements both in the heating and cooling seasons were within the thresholds suggested by the standards. In addition, the PMV method suggested that only 4% of the occupants were dissatisfied with the indoor environment. However; the actual dissatisfaction ratio of occupants was 100% under these indoor environmental conditions. The findings of this study show that predefined comfort ranges, and, thus thermal comfort standards are not able to predict occupant thermal dissatisfaction.

Keywords: Thermal complaint; PMV-PPD model; thermal comfort; ISO 7730

1. Introduction

Thermal comfort is stated as an important part of the built environment that affects not only health and wellbeing but also productivity of occupants. Therefore, maintaining a comfortable and satisfactory thermal environment for occupants is one of the main concerns of facility managers. Today, buildings are generally operated according to the thermal comfort standards such as American Society of Heating, Air conditioning & Refrigeration Engineers, US [1] and ISO Standard 7730 [2]. Both standards use the predicted mean vote (PMV) and predicted percentage of dissatisfied (PPD) indices to assess thermal comfort conditions in indoor environments. Since the PMV-PPD model recommends that a narrow temperature range be applied equally across all building types, climatic zones and population, the prediction accuracy of PMV and PPD indices has been questioned by many researchers. Studies conducted in hot and humid climatic conditions prove that the PMV-PPD model tends to over-predict the perceived warmth in the built environment [3–6]. Furthermore, thermal comfort complaints have been reported in different types of buildings [3,7–11]. However, these studies should also check the compatibility of indoor environmental

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conditions against the standards along with the analysis of thermal complaints. This study aims at investigating the compatibility of indoor environmental conditions against ISO 7730 Thermal Comfort Standard in a commercial building as well as analysing the thermal complaints obtained from the occupants. The following sections introduce the material, present the methodology, provide results and conclusion.

2. Material

The study was conducted between January 2017 and May 2018 in a commercial building located at the West of Paris, France. A total of 17 ambient sensors were used to monitor the indoor air temperature (T) and relative humidity (RH) on the second floor of the building. The data was collected at a 10 mins frequency. The floor consists of two open space offices, one corridor, two small meeting rooms for two persons, one meeting room for 8 persons and two enclosed offices. In addition, a closed-ended survey was used to characterize the kinds of issues occupants complained about in the demonstration zone and the prevalence of these complaints in relation to building systems. The survey data contains (i) timestamp of the demand, (ii) the type of location (i.e. open space office) of occupants, (iii) the domain of the building system (i.e. HVAC, lighting) and (iv) the type of complaint. A total of 53 complaints in relation to HVAC system are analyzed. Since thermal comfort standards recommend different ranges for the heating and cooling seasons, complaints were analyzed separately. A total 29 (~55%) and 24 (~45%) out of 53 thermal complaints were analyzed for the heating and cooling seasons, respectively. It should be noted that on some particular dates more than one occupant has filed a thermal complaint. Accordingly, the timestamp of the filed complaints was taken into account to find the corresponding operative temperature and relative humidity ratios.

3. Methodology

In this study, thermal comfort standards were assessed according to the ISO Standard 7730. This standard suggests the Fanger's model [12] in which the PMV and PPD indices are used for assessing and predicting thermal comfort in indoor environments including buildings [11,13–17]. The CBE Thermal Comfort tool [18] was used to calculate the PMV and PPD indices, in which the input parameters are indoor air temperatures (°C), relative humidity (%), mean radiant temperature (°C), air velocities (m/s), clothing insulation values (clo) and metabolic rate of the users (met). Indoor air temperature and relative humidity ratios corresponding to the complaints in relation to HVAC system were obtained from ambient sensor data. Mean radiant temperatures were calculated by using the formula (Equation 1) proposed by Nagano [19].

$$T_r = 0.99 \times T_a - 0.01,\ R^2 = 0.99 \quad (1)$$

where T_r represents the mean radiant temperature and T_a represents the indoor air temperature. Air velocity was assumed to be 0.15 m/s, which is below the maximum allowable air velocity in offices according to ISO7730 Standard. Metabolic rates and clothing insulation values of occupants were calculated by using the corresponding tables in ISO7730 Standard. Subsequently, the metabolic rate was determined as 1.2 met, which corresponds to office sedentary activities. The checklist of clothing in the ISO7730 Standard was used to obtain the clothing insulation (clo) values, which were determined according to the most likely garments to be worn. Subsequently, the clo values were determined as 0.57 clo and 1.1 clo for cooling and heating seasons, respectively. Moreover, the operative temperature was calculated to check the compatibility of this parameter with the recommended values in the ISO7730 Standard. Equation 2 which is given in the ASHRAE55-2010, is used to calculate the operative temperatures.

$$T_o = A \times T_a + (1-A) \times T_r \quad (2)$$

In the Equation 1, T_o represents operative temperature and A is weighting factor that depends on air velocity (v_r) and was determined as 0.5 according to the ASHRAE55-2010.

4. Results

4.1. Analysis of indoor environmental conditions

This section presents the assessment of indoor environmental conditions against ISO 7730 Standard per heating and cooling seasons. Operative temperature (°C) and relative humidity (%) were taken into account in the analysis. The maximum and minimum allowable operative temperatures recommended by ISO 7730 are 20 °C and 24 °C for heating season, respectively. Fig. 1 shows the distribution of operative temperatures corresponding to the date of the complaints as well as the recommended maximum and minimum allowable values for the heating season. It should be noted that each dot in the following figures represent the measurement of indoor environmental parameter that corresponds to an occupant's thermal complaint.

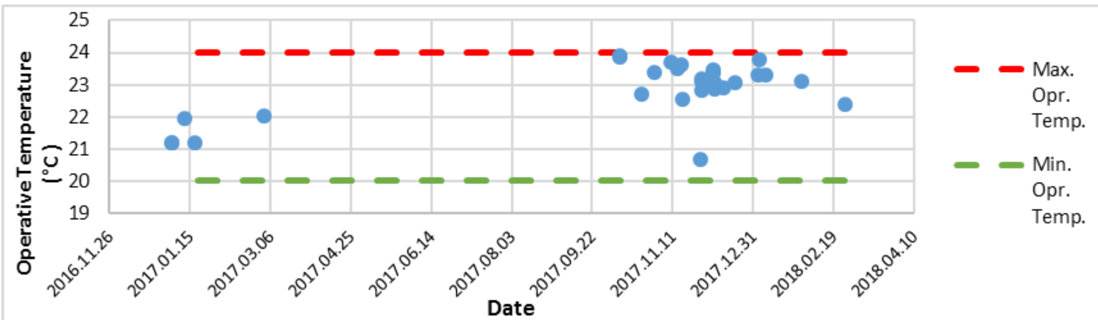

Fig. 1. Distribution of operative temperatures in the heating season

The complaints were collected between January 2017 and May 2018, and, thus, the period covers 2 heating seasons starting from October until the end of March. A total of 24 and 5 thermal complaints out of 29 were collected in the heating seasons of 2017 and 2018, respectively. As can be seen from the figure, all operative temperatures were within the recommended values. The maximum operative temperature was observed on October 9th, 2017 with a value of 23.9°C, which is almost at the maximum allowable operative temperature recommended by ISO 7730 Standard. The minimum operative temperature was observed on November 28th, 2017 with a value of 20.8 °C. Fig. 2 shows the distribution of relative humidity measurements as well as the recommended maximum and minimum allowable values for the heating season. It should be noted that the minimum and maximum allowable relative humidity ratios are 30% and 70% for the heating season, respectively.

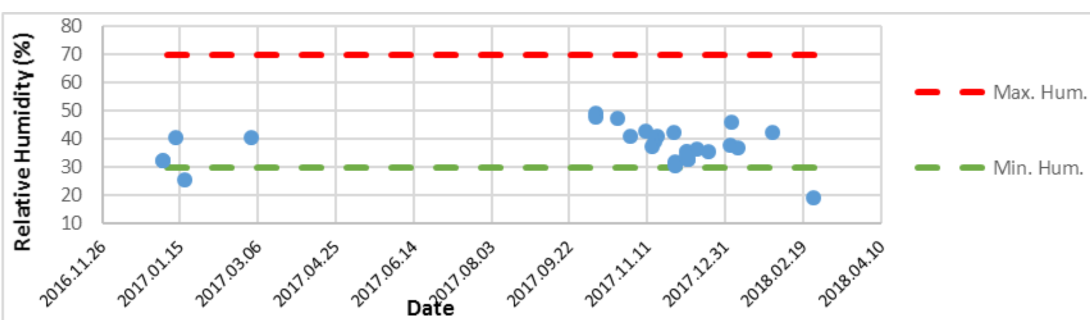

Fig. 2. Distribution of relative humidity ratios in the heating season

As can be seen, 2 out of 29 measurements were below the recommended minimum relative humidity ratios. The minimum relative humidity was observed on January 26th, 2018 with a value of 19.3% whereas the maximum relative humidity was observed on October 9th, 2017 with a value of 49.1%.

Regarding the cooling season, ISO 7730 Standard recommends 23 °C and 26 °C as the maximum and minimum allowable operative temperature, respectively. The complaints were collected between January 2017 and May 2018, and, thus, the period covers 2 cooling seasons starting from April until the end of September. It should be noted that the experimental campaign covered only the months of April and May in the cooling season of 2018. A total of 11 and 13 thermal complaints out of 24 were collected in the cooling seasons of 2017 and 2018, respectively. Fig. 3 shows the distribution of operative temperatures as well as the recommended maximum and minimum allowable values for the cooling season.

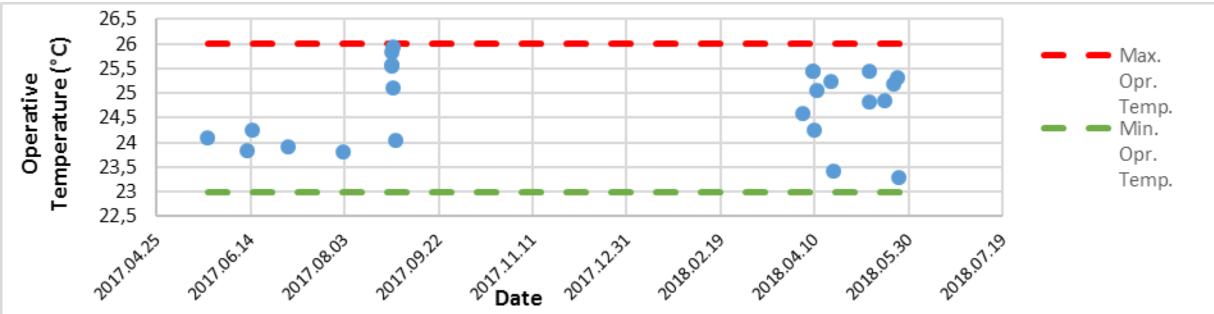

Fig. 3. Distribution of operative temperatures in the cooling season

As can be seen from the figure, all operative temperatures were within the recommended values. The maximum operative temperature was observed on August 28th, 2017 with a value of 25.9°C, which is close to the maximum allowable operative temperature. The minimum operative temperature was observed on May 25th, 2018 with a value of 23.2 °C. Fig. 4 shows the distribution of relative humidity measurements as well as the recommended maximum and minimum allowable values for the cooling season. It should be noted that the minimum and maximum allowable relative humidity ratios are 30% and 70% for the cooling season, respectively.

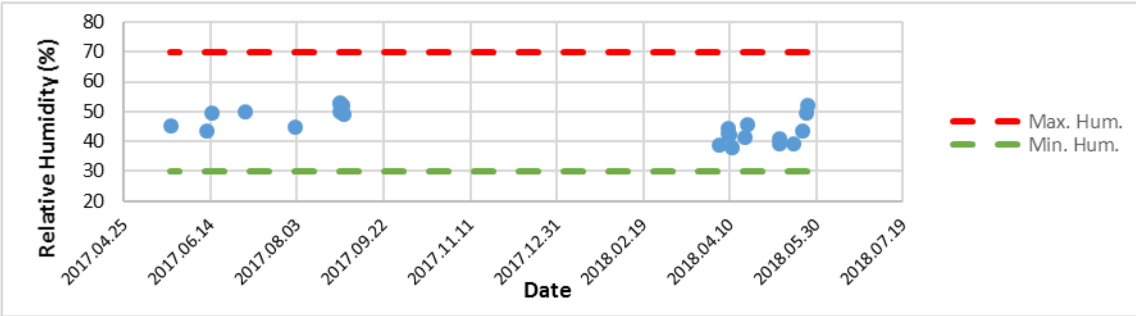

Fig. 4. Distribution of relative humidity ratios in the cooling season

As can be seen from the figure, all relative humidity ratios were within the recommended values. The maximum humidity was observed on August 28th, 2017 with a value of 52.3%. The minimum humidity was observed April 11th, 2018 with a value of 38.0%.

4.2. Comparison of PMV values and thermal complaints

This section investigates the compatibility of PMV and PPD values with ISO 7730 Standard. The maximum and minimum allowable PMV values are -0.5 and +0.5 for both heating and cooling seasons. Fig. 5 shows the distribution of PMV values as well as the recommended maximum and minimum allowable values for both seasons. It should be noted that each dot in Figures 5 and 6 represent the PMV values calculated according the measurement of indoor environmental parameter that corresponds to an occupant's thermal complaint.

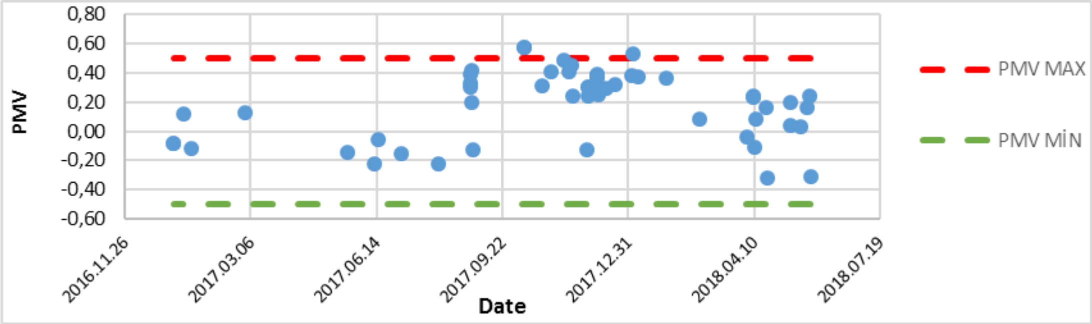

Fig. 5. Distribution of PMV values

The results show that 96% of PMV values comply with ISO 7730 Standard, which means that 96% of indoor environmental conditions are satisfactory for the occupants. In addition, the allowable PPD value is less than %10 for both heating and cooling seasons per ISO 7730 Standard. Fig. 6 shows the distribution of PPD values as well as the recommended allowable values for both seasons.

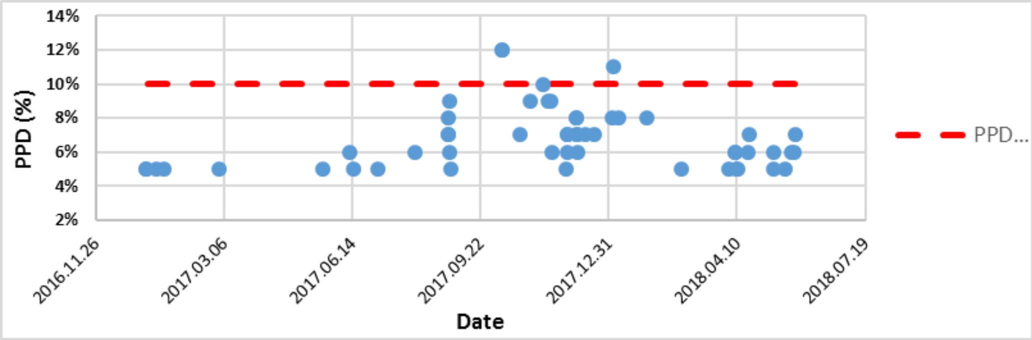

Fig. 6. Distribution of PPD (%) values

The PPD values suggest that there are 2 incidents in which occupants were not satisfied with the indoor conditions. These incidents were observed in the heating season. However, there are 53 thermal complaints filed in these particular conditions. Fig. 7 presents the distribution of thermal complaints filed by the occupants. The results show that occupants have both warm and cold complaints regardless of the season. Therefore, a predefined comfort set point do not ensure occupant thermal satisfaction in the built environment.

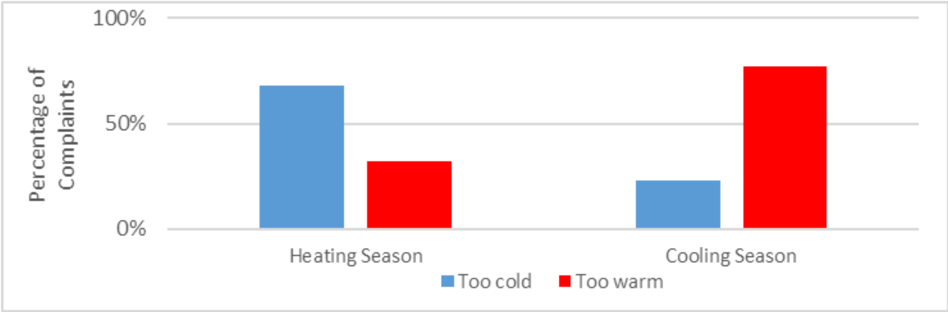

Fig. 7. Distribution of thermal complaints per season

5. Conclusion

In this study, the accuracy of PMV method for predicting occupant thermal satisfaction was checked via assessing thermal complaints of occupants. In addition, the compatibility of indoor environmental conditions against ISO 7730 Thermal Comfort Standard in a commercial building located in Paris, France was investigated. The results show that all of the operative temperature measurements both in the heating and cooling seasons were within the thresholds suggested by the standards. Ninety-three percent and 100% of measurements regarding relative humidity ratios were within the recommended ranges. Furthermore, the PMV values showed that 96% of the occupants felt natural, and, thus, only 4% of the occupants were dissatisfied with the indoor environment. However; the thermal dissatisfaction ratio of occupants under these indoor conditions was 100%. The findings of this study show that predefined comfort ranges do not ensure occupant thermal satisfaction. The limitation of this study is that the findings are based on one building, and, thus, future studies can incorporate more buildings to validate the results of this study.

Acknowledgements

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Empirical Approaches for Assessing Key Factors Pertaining to Greenhouse Gas Emissions in Early Stages of Projects

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Abstract

Since the middle of the 18th century, the entire world has been devoted to industrial development. Based on the development of industry, many countries around the world have achieved rapid economic growth [1]. This resulted not only in economic growth but also a large increase in the amount of greenhouse gases (GHG), which is evident as climate change and environmental disruption. To overcome such adverse effects, this study focuses on assessing the key environmental factors at the early stage of a project for decision makers. To support this objective, the authors have collected 210 real road construction cases and investigated 23 dependent factors including design parameters and physical environment of construction projects. Subsequently, statistical analysis as factor selection and regression modeling is conducted to extract the key factors. As a result, a total of five factors are extracted: “Area of Rice field,” “Total Project Cost,” “Number of Bridges,” “Design (maximum) Speed,” and “Length of Earthwork” via regression analysis. Moreover, the proposed regression model accounts for 69% and 67% of the total variance of “Total Environmental Loads” indicated by R^2 and adjusted R^2, respectively, at 99% of the significance level. Thus, the proposed model is expected to play a positive role in the decision-making process based on mathematical and empirical evidences.

Keywords: Greenhouse gases (GHG); Environmental Variables; Decision Making; Regression model; Planning Phase; Construction Projects

1. INTRODUCTION

Since the middle of the 18th century, the world has been devoted to industrial development resulting in a substantially convenient and abundant life. As a result, many countries in the world are now urbanized, and more than half of the world’s population lives in urban areas [2]. Economic growth is based on the emission of greenhouse gases (GHG) as a result of resource consumption. Thus, rapid economic growth and urbanization are not only the cause of serious pollution and exhaustion of resources, but also a primary factor in the greenhouse effect [1]. National Oceanic and Atmospheric Administration (NOAA) analyzed that the average temperature of the Earth’s surface is constantly rising, and faster changes are observed as modernization accelerates [6].This means that GHG emissions have exceeded the natural purification rate of the earth. Because of climate change, GHG can result in several diseases and damages to human kind. Moreover, climate change gives rise to abnormal conditions which poses threat to our lives. Fortunately,

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the concept of environmental protection is widely spreading to make the earth considerably sustainable. Following this trend, the Kyoto protocol was implemented in 1997 to reduce GHG emissions.
Nevertheless, sustainable growth is faced with problems such as egoism or chauvinism. The agreement was declined in the 17th Conference of Parties (COP 17) at the United Nations Framework Convention on Climate Change (UNFCCC) [7]. COP 17 aimed at new strategies for climate change, but only the renewal of the Kyoto protocol was agreed to. However, some of top emission countries decided and announced that the reject of new Kyoto protocol. Thus, the agreement of COP 17 is flawed in terms of substantial impact. Environment is not a subject of agreements and deals. Thus, new constraint for climate change should be specified at the earliest, and the preparation for sustainable growth is crucial. To control and manage sustainability in case of construction, the assessment of key impact factors is critical. Past research only dealt with cost or performance as the influencing factors. Further, these studies did not consider the aspect of sustainability, and so, their direct application to environmental factors is irrational. Consequently, assessing the key environmental impact factors in construction projects is important.

2. EXPERIMENT

The primary objective of this article is to identify the key factors that impact the environment and compare the results between the key factors of cost impacts in construction projects. In particular, the focus is on a road construction project in various landforms including mountains and river areas. The specific objectives of this study include; (1) examining the relationship between Total Environmental Loads (TEL) including bridging and tunneling works; (2) preliminary assessment of both key factors based on 210 road construction cases; and (3) comparison between both key factors and subsequent analysis of the results. Figure 1 shows the experimental procedure.

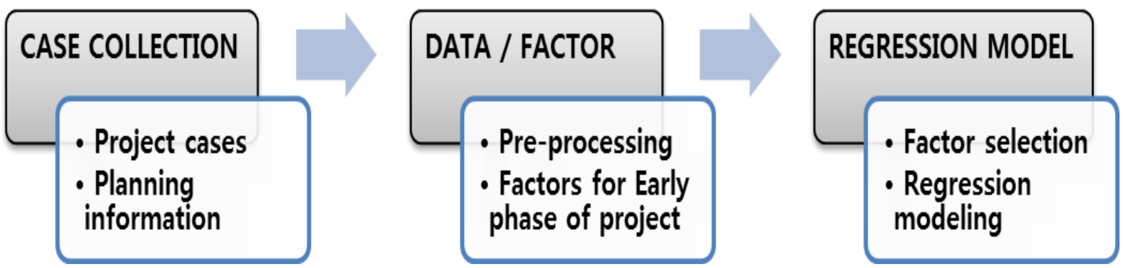

Fig 1. Experimental procedure

2.1 Case Collection

To ensure the reliability of the experiment, the authors collected several cases of road construction projects. Consequently, data for a total of 210 project cases were collected, which include the detailed information of the projects. Table 1 presents the nature of the collected cases. First, several projects are located in mountainous areas; mountainous areas are a regional characteristic of Korea, with more than 70% of the territory being in mountainous areas. Further, a few of the projects are located in the downtown area, which is a characteristic of the expressway that connects provinces or cities.

Table 1. Nature of collected project

Category	Section	Rate (%)
Site	Downtown	3.8
	Mountain	62.6
	Plain	33.6
Length	Under 5 km	20.9
	5–10 km	49.9
	Over 10 km	32.2
Contract sum	Under 50 billion	30.3
	50–100 billion	40.3
	Over 100 billion	29.4
Owner	Public	90
	Private (including PPP)	10

2.2 Regression Model

This study aims at developing a prediction model for decision makers. Further, it aims to support the conceptual planning phase of projects. Thus, the authors investigate the factors focusing on the collectable data in the early phase of a project from the collected projects including the bill of quantity (BOQ) and proposal report of each project. Using this process, a total of 23 factors that can represent the nature of the construction projects at the early phase were identified. Table 2 lists the details of these factors. Subsequently, the authors obtained the key impact factors using factor analysis and set up the regression model using SPSS program.

Table 2. Descriptions of factors

Codes	Description	Codes	Description
F1	Type of Construction	F13	Site location_ Plain
F2	Regional Characteristics	F14	Farm area
F3	Number of lanes	F15	Rice field area
F4	Width of lanes	F16	Plot area
F5	Total length of Roads	F17	Mountain area
F6	Length of Earthwork	F18	Total Area
F7	Level of Roads	F19	Number of Bridge
F8	Design (maximum) Speed	F20	Total length of Bridge
F9	Radius of Horizontal Curve	F21	Number of Tunnel
F10	Maximum Incline	F22	Total length of Tunnel
F11	Site location_ Down town	F23	Total Project Cost
F12	Site location_ Mountain,		

In details, all factors were investigated from BOQ and proposal of projects that have various scales and dimensions. Generally, factors are categorized in two sections such as dummy and independent variables. Total 7 factors are categorized as dummy variables i.e., F1, F2, F3, F7, F11, F12, and F13. Other factors are categorized as independent variables. Nevertheless, a total 103 cases can satisfy this information among the total 210 cases. Thus, to reduce the bias from missing or incomplete data set, the authors used only 103 cases to set up the regression model. After factor selection, the authors performed a regression analysis. Consequently, five factors were extracted as F15, F23, F19, F8, and F6. Each of the factors is highly significant at the 99% significance level. Table 3 shows the results of the regression analysis.

Table 3. Results of regression analysis

	Coefficient	SE	t	Sign.
(Constant)	-66616	22984	-2.89	0.005
Rice field area	0.070	0.23	3.06	0.003
Total Project Cost	0.000004	.000	5.75	0.000
Number of Bridge	-6450	2189	-2.94	0.004
Design (maximum) Speed	1119	304	3.67	0.000
Length of Earthwork	2.783	0.886	3.14	0.002
N	103			
R^2	0.693			
Adjusted R^2	0.677			

* SE; Standard Error, t; t-Statistics, Sign; Significance, N; Number of samples

3. DISCUSSIONS AND CONCLUSIONS

This paper deals with the assessment of key impact factors for construction project from an environmental perspective. Moreover, it also focused on the early phase of project (conceptual planning phase). To achieve these objectives, first, the authors collected 210 real project cases. Subsequently, they identified the related factors regarding TEL (Total

Environmental Loads). After data processing, the authors applied SPSS program for variable selection and regression analysis. Through variable selection, correlated and overlapped factors were eliminated. Finally, regression model was suggested for TEL estimation. Statistically acceptable results are obtained via R^2 (0.693) and adjusted R^2 (0.677) considering that the previous researches suggested 30% to 50% of error rate at the early phase of a project [3] [4] [5]. However, this paper has certain limitations with regard to the use of simple statistical approach, and bias of data, which composed of Korean projects. However, it will be considered in future research. Despite these limitations, this paper analyses 210 real construction cases focusing on road project and satisfies the general range of expectations. Thus, it is expected to play a positive role in the decision-making process based on mathematical and empirical evidences.

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Employing generative design for sustainable construction

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Abstract

Generative design is the alteration of an object's shape to optimize its function. Currently, the scope of generative design is limited in the structural civil engineering field. Structural design still follows conventional methods compatible with conventional construction processes. These processes restrict the flexibility in design resulting in structural elements having excess materials to satisfy critical structural capacity requirements. This introduces additional costs and higher environmental impacts. New tools, such as concrete and steel 3D printers, are emerging to enable more complex geometries in construction allowing higher flexibility in design options. Inspired by the above, this paper aims at developing a design engine that provides optimal design solutions to reinforced concrete beams with sufficient structural capacities while using less materials and resources. Based on ACI code design guidelines, a cantilever beam was structurally analyzed to relate geometry parameters to structural capacity. Optimization was achieved by minimizing the depth and the steel reinforcement ratio at each segment along its length. Hence, concrete and steel at each location would take their optimal quantities. This results in lighter and more economic structures conforming to the structural capacities required by the codes. The engine is based on three objective functions that solve for the minimum values of beam depth and reinforcement at each section which optimize cost and CO_2 emissions individually or simultaneously. MATLAB was used to design the optimized beam and to calculate the percentage decrease in cost and CO_2 emissions between the optimized and conventional beam. A significant reduction ranging between 40% and 52% of cost and between 39% and 51% of CO_2 emissions per beam is achieved. If the design engine developed was utilized in parallel with the 3D printing construction method, structures with optimized quantities, materials, and shapes would be developed. Thus, minimizing drastic effects on the environment and achieving reduced costs.

Keywords: 3D printing construction method; CO_2 emissions optimization; cost optimization; generative design; structural analysis

1. Introduction

Generative design is being addressed in the automotive and architectural fields by changing an element's shape to optimize its function. However, the structural engineering field lags in this area where structural engineers continue to use methods established approximately 100 years ago [1,2]. Generative design systems aim to create design processes that produce more efficient shapes by exploiting current computing and manufacturing capabilities [3]. Such systems are inspired from nature by accepting and rejecting design options to get a form that uses precise amounts of materials

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where required, to eventually create optimized structures that meet or exceed traditional capabilities [4]. Similar processes of imitating nature's strategies are called biomimicry [5].

Optimization approaches with defined objectives and constraints are employed through computer algorithms to achieve such structural improvements [6]. Optimization techniques fall into three categories: mathematical, optimality, and heuristic programming methods, each of which has its applications and limitations [6].

With the quick advancement in 3D printing technologies, shape optimization has become the interest of not only manufacturers but also anyone who has access to a 3D printer [7]. One of the main advantages that concrete 3D printing provides over the conventional construction method is that the concrete does not need an existing formwork [8]. In fact, optimized concrete structures are best constructed using 3D printing technology where the designed geometry meets structural requirements while consuming the least possible construction resources [7]. As for steel 3D printing, Arc welding is considered the most efficient additive manufacturing technique [9]. These methods are mainly entitled to push the boundaries and constraints of the design world that are available for engineers and architects [8].

This research aims at generating an optimized structural element (singly reinforced cantilever beam) by reducing materials' quantities; thus, reducing its environmental footprint and cost. The scope was set to develop an engine that provides optimal design solutions to reinforced concrete beams having sufficient structural capacities and utilizing fewer resources. The variables studied are the depth of concrete and the steel reinforcement ratio. Moreover, employing 3D printing for the construction process in such context was examined.

To achieve the study objectives, an optimization process was applied to a cantilever beam to explore its effects on design parameters and consequently cost and CO_2 emissions. For comparison purposes, the implications were checked for a non-optimized cantilever beam.

2. Methodology

The project is divided into two parts: developing a design engine and evaluating the 3D printing construction process. To develop the design engine, the following methodology was adopted: defining the design variables, performing theoretical structural analysis, building the engine through MATLAB coding, and realizing the outputs.

2.1. Problem description and design steps

Two cantilever beams were studied. The first is the reference beam, which is designed by the traditional methods, while the second is the beam with varying cross section, which is designed considering optimization techniques as shown in Fig. 1 (a) and Fig. 1 (b) respectively.

Focusing on the optimized beam design, the structure was analysed by basic flexural design methods to determine the required concrete depth h and steel reinforcement ratio at each section (considering a uniform incremental length x across the entire length L as presented in Fig. 1 (b)). Shear design was performed to determine the area of shear reinforcement needed for each region. Deflection checks based on maximum permissible deflections suggested in Table 9.5 (b) in the ACI code were conducted [10]. Long term deflection is reduced by adding compressive steel [10]; however, after checking deflection, it was realized that there is no need to add compressive steel.

The study considers a singly reinforced cantilever beam with varying depth h (m) and steel reinforcement ratio ρ as shown in Fig. 1 (b).

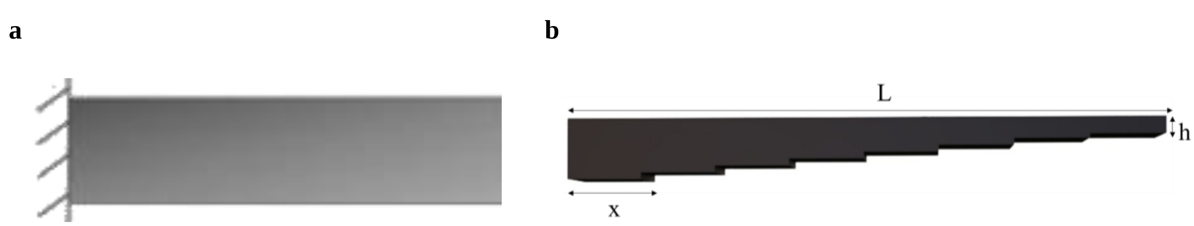

Fig. 1. (a) traditionally designed beam; (b) optimized beam.

The length L (m) and width b (m) of the beam are user defined parameters. The structure is subjected to a uniformly applied load including superimposed dead load SDL, live load LL and self-weight of the beam. The total dead load DL is the sum of the SDL and self-weight. Based on typical applications, the considered SDL and LL are 200 (kg/m^2) and 250 (kg/m^2) respectively. The load combination employed is $1.2 \times DL + 1.6 \times LL$ [10]; however, since the self-weight is varying along the length of the beam the constant distributed load C (kg/m), excluding self-weight, would be as calculated in (1).

$$C = TA \times (1.2 \times SDL + 1.6 \times LL) \quad (1)$$

The corresponding ultimate design loads: bending moment M_u and shear force V_u acting on the critical section of the beam were calculated. A sample equation for a beam divided into two sections is shown in (2) and (3).

$$M_{u(2)=} \frac{1}{2} C \left[x_{(1)} + x_{(2)}\right]^2 + \gamma b (h_{(1)})(x_{(1)}) \left(x_{(2)} + \frac{x_{(1)}}{2}\right) + \gamma b (h_{(2)})(x_{(2)}) \left(\frac{x_{(2)}}{2}\right) \quad (2)$$

$$V_{u(2)=} [C + 1.2 \gamma b (h_{(2)})] \quad (3)$$

Where $x_{(1)}$, $h_{(1)}$, $x_{(2)}$ and $h_{(2)}$ represent the length and depths of sections one and two respectively. All remaining variables and parameters mentioned in (2) and (3) in addition to other parameters are described in Table 1.

2.2. Design variables and parameters

The design variables are the beam depth and the ratio of steel reinforcement. The parameters that are set as inputs into the code include: L, b, increment length x, and TA. Table 1 includes all the design parameters, defined as constants during the optimization process. The values are those used by common reinforced concrete design practice or as depicted by the ACI code [10]. Also, Table 1 includes the necessary design equations used to calculate parameters referred to in other sections of the paper [10].

Table 1. Design parameters and corresponding values and equations.

Parameter	Value	Parameter	Equation
Concrete compressive strength	$f_c{}' = 280 \times 10^4$ (kg/m^2)	Effective depth of the beam	$d = h - 0.05$ (m)
Reinforcement yield strength	$f_y = 4200 \times 10^4$ (kg/m^2)	Area of flexural steel reinforcement	$A_s = \rho \times b \times d$ (m^2)
Specific mass of reinforced concrete	$\gamma = 2500$ (kg/m^3)	Nominal moment capacity	$M_n = A_S \times f_y \times (d - \frac{\rho \times (h-0.05) \times f_y}{2 \times 0.85 \times f_c{}'})$ (kg.m)
Specific mass of steel	$\int_s = 7.8 \times 1000$ (kg/m^3)	Spacing of shear reinforcement	s (m)
Strength reduction factor for shear	$\emptyset = 0.75$	Nominal shear strength provided by concrete	$V_c = 2\sqrt{f_c{}'} \times b \times d$ (kg)
Strength reduction factor for flexure	$\emptyset = 0.9$	Nominal shear strength	$V_n = \frac{V_u}{\emptyset}$ (kg)
	$\beta_1 = 0.85$	Nominal shear strength provided by shear reinforcement	$V_s = V_n - V_c$ (kg)
Tributary area	TA (m)	Area of shear reinforcement	$A_v = \frac{V_s}{d \times f_y} \times s$ (m^2)
Concrete cover	5 cm		

2.3. Optimization problem and solution method

Two MATLAB optimization solvers were used: “fmincon” and “gamultiobj”. “fmincon” function follows the Lagrangian Multiplier Method (mathematical programming method) which is capable of performing optimization for constrained complex engineering problems [11], whereas “gamultiobj” uses a controlled elitist genetic algorithm (heuristic method) that favors fitter individuals [12]. “fmincon” performs constrained nonlinear multi-variable optimization that requires an initial estimate to find a constrained minimum of an objective function [13,14]. Two objective functions were considered separately: one minimizes cost and the other minimizes CO_2 emissions to yield optimized depth and reinforcement values. Another scenario of considering both objectives simultaneously was also evaluated. Such a scenario is not permissible using Lagrangian optimization, therefore a genetic algorithm which allows multi-objective optimization was used [12].

The objective functions corresponding to the minimization of cost and CO_2 emissions are (4) and (5) respectively. Table 2 summarizes cost estimates that are based on common practice in Lebanon, and CO_2 emissions in reference to [15].

Table 2. Cost and CO_2 footprint of concrete and reinforcing steel.

Material	Cost	CO_2	Quantity
Concrete ($fc' = 40$ MPa)	80 ($/m^3)	518.23 (kg/ m^3)	$b \times h \times increment$ (m^3)
Steel	600 ($/ton)	7.4 × 1000 (kg/ton)	$\int_s \times \rho \times b \times d \times increment$ (ton)

$$f_1 = (Cost_c \times Volume_c) + (Cost_s \times Mass_s) \quad (4)$$

$$f_2 = ((CO_2)_c \times Volume_c) + ((CO_2)_s \times Mass_s) \quad (5)$$

Where subscripts c and s correspond to concrete and steel respectively.

Serviceability and strength constraints based on the ACI code were considered for the optimization process [10]. Serviceability constraints include maximum allowable deflection (m): $\frac{L}{480}$ (6). Strength constraints include: flexural strength according to moment capacity (7), minimum and maximum requirements for flexure reinforcements (8), (9), (10) and (11). The minimum height h_{min} of concrete considers minimum reinforcement and cover. As recommended in [16] the maximum height $h_{\max}$ of concrete is the width multiplied by 2.5.

$$|M_u| < 0.9 \times M_n \ (kg.m); \ \ \forall increments \left(\frac{x}{L}\right) \quad (7)$$

$$h_{min} = 0.1 \ (m) \quad (8)$$

$$h_{max} = 2.5 \times b \ (m) \quad (9)$$

$$\rho_{min} = minimum\ of\ \left(\frac{3\times\sqrt{f_c{}'}}{f_y}\ or\ \frac{200}{f_y}\right) \quad (10)$$

$$\rho_{max} = \frac{0.85\times\beta_1\times f_c{}'}{f_y}\left(\frac{87000}{87000+f_y}\right) \quad (11)$$

The variables in these equations were defined in text of section 2.1 and Table 1.

3. Results of optimal design

The optimization process was explored for several cantilever beams having varying lengths L and widths b and subject to different loads. Additionally, non-optimized solutions characterized by a constant cross section were obtained for beams with similar parameters for comparison purposes. The results corresponding to a sample structure of a 4 (m) long beam having a width b of 0.3 (m) and carrying an area of 8 (m^2), will be elaborated in this section. The geometry resulting from the optimization process differed among the different objective functions. In each of these, the depth h and the ratio of reinforcement ρ converged to the optimal solution that minimizes the respective objective functions. Table 3 summarizes the obtained results.

All objective functions considered yield a much lower concrete volume than that obtained through the traditional approach but a higher total mass of steel reinforcement. These optimum results were also associated with a significant lower cost and CO_2 footprint. The different total volume and mass are a consequence of different combinations of depth h and ratio of reinforcement ρ at each section to minimize each respective objective function. It can be noticed that the objective function minimizing cost alone results in the least total concrete volume and the largest reinforcement mass, while that minimizing the CO_2 footprint results in a higher concrete volume but lower reinforcement. Results emerging from the multi-objective function solution compromise the outcomes.

Additionally, as the increment size decreases a more optimized solution is achieved as observed in Table 3 and Fig. 2. For example, the results of the cost objective function improved by 9% in terms of volume reduction and 23% in terms of reinforcement mass reduction when the increment size was reduced from 1 (m) to 0.01 (m). This reduction was also associated with a reduction of cost and CO_2 footprint by approximately 25% each. All the outputs of the optimization process related to the flexure design are represented in Table 3 below for the non-optimum solutions and for each objective function and increment size. Results for shear and deflection were also obtained as a part of this study but are not presented in the table. Fig. 2 below shows the variation of cost and CO_2 footprint as the size of the increment increases or as the number of sections that subdivide the beam decreases. A significant reduction in cost and CO_2 footprints is achieved ranging between \$23 and \$30 and 196 and 257 kg of CO_2 per beam.

		Depth (m)		Reinforcement Ratio		Concrete Volume (m^3)	Reinforcement Mass (tons)	%Cost Reduction	%CO_2 Reduction
Conventional (Not Optimized)		0.481		0.007		0.577	0.028	-	-
Increment Size	Objective Function	Edge	Support	Edge	Support				
	Cost	0.125	0.360	0.012	0.012	0.290	0.022	41.85	38.75
1	CO_2	0.141	0.428	0.008	0.008	0.340	0.017	40.19	39.86
	Cost + CO_2	0.142	0.421	0.008	0.008	0.327	0.018	40.76	39.71
	Cost	0.100	0.359	0.006	0.012	0.268	0.019	47.19	44.70
0.5	CO_2	0.100	0.427	0.006	0.008	0.312	0.015	45.78	45.72
	Cost + CO_2	0.100	0.370	0.006	0.008	0.286	0.017	46.73	45.28
	Cost	0.100	0.358	0.003	0.012	0.258	0.018	49.62	47.38
0.25	CO_2	0.100	0.426	0.003	0.008	0.299	0.014	48.29	48.36
	Cost + CO_2	0.100	0.395	0.003	0.008	0.279	0.016	49.05	48.04
	Cost	0.100	0.358	0.003	0.012	0.252	0.017	51.05	48.96
0.1	CO_2	0.100	0.426	0.003	0.008	0.292	0.014	49.78	49.91
	Cost + CO_2	0.102	0.359	0.003	0.008	0.271	0.015	50.54	49.58
	Cost	0.100	0.358	0.003	0.012	0.250	0.017	51.52	49.47
0.05	CO_2	0.100	0.426	0.003	0.008	0.289	0.014	50.27	50.42
	Cost + CO_2	0.100	0.392	0.003	0.008	0.264	0.016	51.17	49.95
	Cost	0.100	0.358	0.003	0.012	0.248	0.017	51.89	49.88
0.01	CO_2	0.100	0.425	0.003	0.008	0.287	0.013	50.66	50.83
	Cost + CO_2	0.100	0.405	0.003	0.008	0.264	0.015	51.49	50.40

Table 3. Design variables of results for optimized and non-optimized solution.

4. Discussion

According to Table 3, the optimized beam resulted in a cost decrease that ranged from 40% to 52%. If this optimization process is applied to all similar beams in a building, its impact would be more tangible. Additionally, if such optimization processes are adopted in the design of other types of structural elements in a building the effect on cost reduction would be substantial. Also Table 3 shows that the CO_2 percentage decrease ranged between 39% and 51%

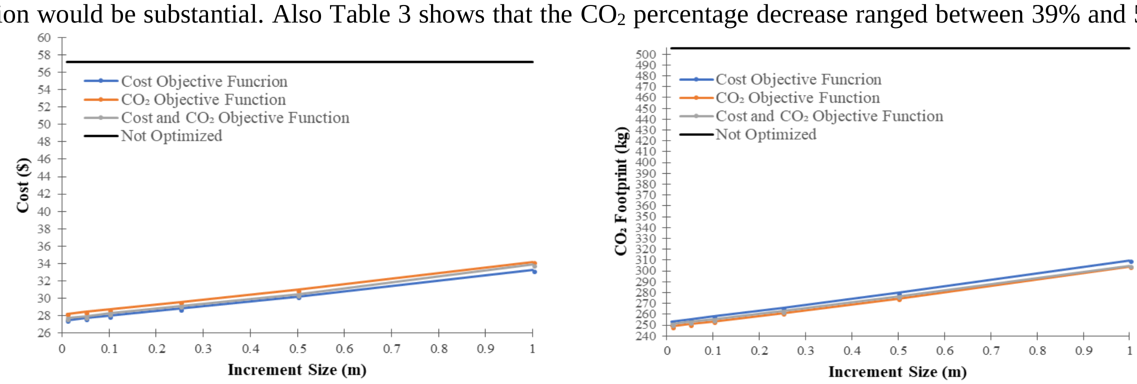

Fig. 2. (a) change in cost with increment size; (b) change in CO_2 footprint with increment size.

a **b**

using the CO_2 objective function. A traditionally designed beam produces around 550 kg of CO_2, whereas an optimized beam can decrease this amount to 249 kg; saving almost 301 kg of CO_2 per cantilever beam. Energy used in cement production accounts for 5% of the earth's greenhouse emissions [17]. Saving up to 45% of CO_2 emissions in the optimized design represents a significant benefit regarding greenhouse emissions. If the optimized beam was constructed using the conventional construction process, it would be time exhaustive and more complicated for laborers due to the complex beam geometry (Fig. 1 (b)). However, recent construction methods such as concrete and steel 3D printing facilitate the construction of such structures. Thus, the advantages related to time, quality and cost of such method are discussed along with its recent status in the construction industry.

Time is directly correlated with the interest paid to finance the project [18]. According to El Sakka & Hamzeh, a total of 60% reduction in construction time can be achieved if 3D printing methods were used [18]. In the conventional process, there is frequent labor movement to transport materials and resources such as forms and steel bars, thus generating waste. However, using 3D printing, such waste is eliminated since it is a form free process [18]. Additionally, due to its form free nature, concrete 3D printing minimizes defects such as honeycombing and segregation [18]. Hence, providing improved quality. Similar concrete defects cannot be addressed until formwork stripping occurs whereas in 3D printing such defects can be addressed in an extruded layer before casting the next one [18]. From a financial perspective, this construction method requires less labor because one 3D printer operator can substitute an entire crew [18]. However, this operator requires a certain set of skills and therefore would have a higher wage than a regular labor [18]. Also, since the construction process requires less time, a significant cut down in salaries and overhead costs would be achieved [18]. Yet, the high cost of concrete printers is a current disadvantage; thus, a thorough study should be performed on the direct cost of a concrete 3D printer to study the life cycle cost of this technology.

5. Conclusion

In this study, structural optimization was performed on a RC cantilever beam in order to design low cost and low carbon footprint RC structures. This was achieved by segmenting the beam and minimizing concrete and steel quantities at each section. Primary results yielded cost reduction ranging between 40% and 52%, while CO_2 reduction ranged between 39% and 51%. Also, considering the construction process, optimized structures can be executed by 3D printing construction methods which are considered to be more efficient and environmentally friendly. Current results seem very promising; a reason for efforts to be exerted to scale this work into entire buildings. Further research can follow this logic into other structural elements to eventually achieve optimized structures, and consequently realize greater economic and environmental advantages.

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Energy Retrofitting of a Commercial Building Towards a" Net Zero Energy Building" by Simulation Model

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Abstract

Energy is one of the major drivers of a growing urban infrastructure development. The consumption of energy by different sectors of urban infrastructure are very high and the amount of energy produce is not enough to meet the huge demand of energy. According to several types of research, it is found that building sector is consuming about 40% of energy which is very significant. For heating and cooling of building sector 32% energy is used and its major impact is greenhouse gas emission. This study presents a simulation model that combines building properties and energy consumption of an existing commercial Building in Ahmedabad city (India). This research targets to study how to integrate active design strategies and energy-efficient building materials to improve the building performance and reduce energy consumption towards Net Zero Energy Building (NZEB). This research will suggest few changes in materials of building will be considered as retrofitting and it can lead to the concept of Net Zero Energy building (NZEB). For the analysis and simulation of energy, Design- Builder software is used.

Keywords: *Energy Retrofit; Net Zero Energy Buildings (NZEB); Commercial Building; Building Envelope; Simulation*.

1. Introduction

Energy is a basic requirement for economic development in almost all major sectors of Indian economy-agriculture, industry, transport, commercial, and residential. In India, 33% of the total energy is used by the buildings, out of which 24% by residential and 9% commercial as shown in Figure 1. Buildings are one of the major consumers of energy and are the third largest consumers of energy, after industry and agriculture.

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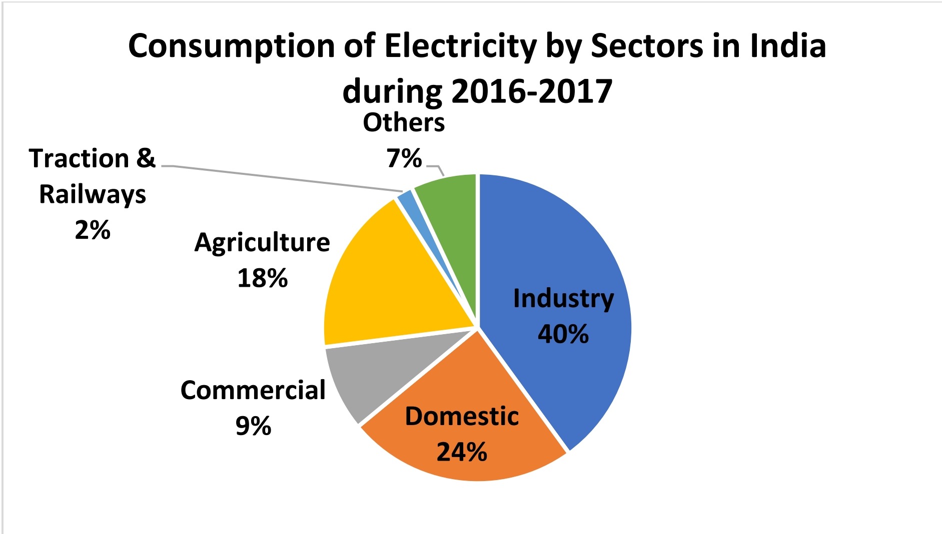

Figure 1. Consumption of Electricity by Sectors in India during 2016-2017

The absolute figure is rising fast, as construction booms, especially in developing countries such as India. Currently, approximately 659 million m² spaces are used as commercial space and in 2030, it is estimated that it would increase to 1,900 million m² and by then more than 60% of the commercial built space would be air-conditioned as shown in Figure 2. [1]

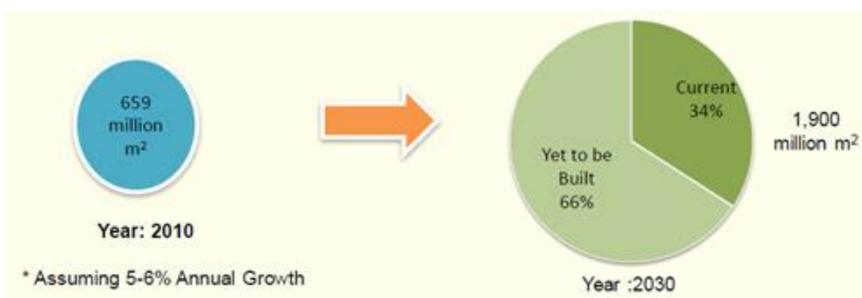

Figure 2. 66% building stock is yet to be constructed

Mentioning the harmful emissions in India, the CO2 per capita emissions reached 1.73 Metric ton/year in the latest [2]. For this reason, the building sector represents a large potential for significantly reducing energy demand and harmful emissions.

In commercial buildings, the high demand for energy used for lighting, heating, ventilation, and air conditioning leads to a significant amount of carbon dioxide emissions. To control this escalating reliance upon fossil fuels and tackle future climate change, it is important to apply effective techniques to upgrade the existing commercial buildings, developing energy efficient commercial buildings based on the integration of advanced energy-saving concepts and adaptive reuse methods. On one hand, taking Net-Zero Energy Building (NZEB) concept into commercial retrofits will improve the energy efficiency levels in existing commercial buildings, exploring the possibilities of involving renewable energy sources in order to reduce their dependence on external energy infrastructure. On the other hand, since the life of commercial buildings is extended and possible demolition waste is avoided, net-zero energy commercial retrofits also contribute to the development of a sustainable urban regeneration form [3].

The idea of NZEB has been widely explored and implemented during the last few years as a way to achieve energy efficiency in the building sector and encourage renewable energy incorporation on-site. “Net or nearly zero site energy buildings (NZEB) are highly efficient buildings with extremely low energy demand, which is met by renewable energy sources. Such buildings produce as much energy as they consume, accounted for annually” as shown in Figure 3.

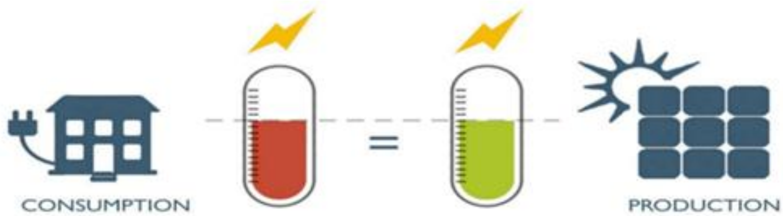

Figure 3 “Net Zero Site Energy Concept”

Through reusing and upgrading existing buildings, the performance of the existing commercial buildings can be improved, thus bringing more opportunities to reinvigorate the large stock of existing commercial buildings and benefit local economies in the long run. Typically, achieving net-zero energy goals can be realized through improving building enclosures, implementing passive design strategies, installing high-performance HVAC systems to reduce heating and cooling loads, reducing lighting and other electric loads, thus making it possible to offset the required energy balance with renewable means, such as solar photovoltaics or wind turbines. Achieving net-zero energy goals is a challenging objective, especially when it comes to retrofit projects, because more constraints are typically imposed on existing buildings than new construction. This paper presents the effective ways to address those physical and economic constraints in commercial retrofits and investigates applicable strategies to achieve NZEBs [3].

Energy-efficient measures, applied to existing buildings during minor/major retrofits, reducing their energy consumption, building envelopes can be grouped into three categories:

1. wall thermal insulation and thermal mass
2. windows/glazing (including day- lighting)
3. reflective roof /green roofs

This study examines the potential of retrofitting an office building in order to become NZEB using DESIGN BUILDER software.

2. Methodology

Firstly, make the present building in DESIGN BUILDER software and simulate its energy consumption was examined. The second step was the minimization of energy consumption applying energy-efficient measures. Finally, the minimized energy was covered applying renewable energy technologies on the building in order to achieve the conversion of the present building into NZEB Figure 4.

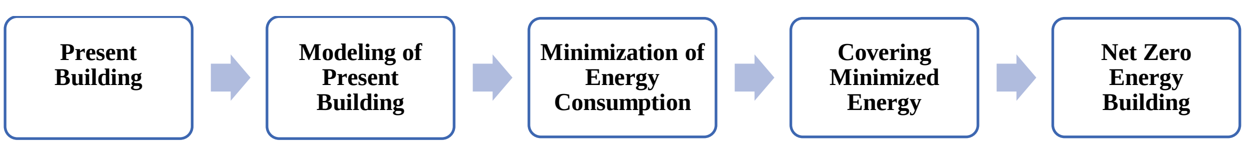

Figure 4 Step of the Project

The minimization of energy consumption requires the application of energy-efficient measures. Energy-efficient measures can be classified into three categories: measures which could be applied in building envelopes. Four scenarios were examined aiming at minimizing the energy consumption of the building and three more in order to cover this minimized energy with renewable energy technologies. Those scenarios are presented in Table 1.

Table 1 Description of Scenario

Description of Scenarios			
Scenario – 1	Combination of following improvements on building envelopes	Insulation on Walls	Replacement of Windows
Scenario – 2	Combination of following improvements on building envelopes	Insulation of Ceiling	
Scenario – 3	Combination of Scenario 1 & 2		
Scenario – 4	Installation of Photovoltaic Panels		
Scenario – 5	Combination of Scenario 3 & 4		

3. Case Study

3.1 Description of the study area

The building IB Law House located in the Navrangpura, Ahmedabad, Gujarat, India. For Indian climate, the comfort range of still air corresponds to 23-41 ºC dry bulb temperature with 30– 60% relative humidity. In India Winter, occurring from October to February then Summer season, from April to June and Monsoon or rainy season, from July to September.

Ahmedabad's comes under the mostly hot & dry or all year round. Ahmedabad's Mean Monthly temperature (ºC)>30, its Relative Humidity>50.

Weather Data Sources: -

This report illustrates the typical weather station at Sardar Vallabhbhai Patel International Airport, based on hourly weather reports and model reconstructions from January 1, 1980, to December 31, 2016.

Temperature: -

The hot season occurs in 3 months, from April to June, with an average daily high temperature above 38°C. The hottest month of the year is May, with an average high of 42°C and low of 28°C. The cool season occurs in 3 months, from December to February, with an average daily high temperature below 30°C. The coldest month of the year is January, with an average low of 13°C and a high of 27°C as shown in figure 5.

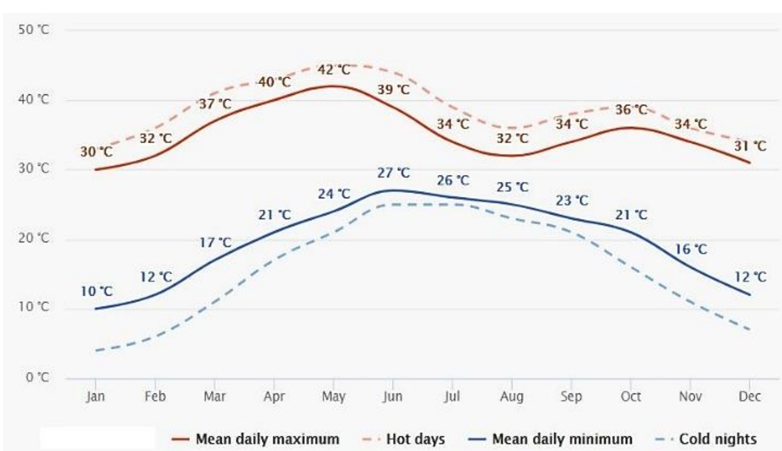

Figure 5 Average High and Low Temperature

The "mean daily maximum" (solid red line) shows the maximum temperature of an average day for every month for Ahmedabad. Likewise, "mean daily minimum" (solid blue line) shows the average minimum temperature. Hot days and cold nights (dashed red and blue lines) show the average of the hottest day and coldest night of each month of the last 30 years as shown in figure 5.

3.2 Building data gathering

The building IB Law House is situated in the Navrangpura, Ahmedabad, Gujarat, India, its coordinates are 72.57° Longitude 23.03° latitude. The building was constructed in 2011 and it is a two-story building with a total height of 10.50m and total length of 20m.

The ground floor (258 m^2) and the first floor (262 m^2) consist of two main offices, entry lobby, waiting hall, two prayer room, conference room, record room, toilets, and pantry room. The second floor (34 m^2) accommodates for the storage area, toilet, and stair cabin as no employees work there. The building has ground floor, first floor and second floor with terrace with a total 28 numbers of zones, 12 numbers of zones are fully air-conditioning and others are naturally ventilated.

Building operating schedule is from 10:00 am until 7:00 pm every day only Sunday close, office work is light work such as typing, consulting, meeting, it can include internal corridors providing access to the office space, tea/coffee making facilities or kitchenettes within the office space and also area for photocopiers, building general information is shown in Table 2.

Table 2 Building summary

	Description
Location	IB Law House, Navrangpura, Ahmedabad, Gujarat
Orientation	West East (WE)
Use	Office Facility
Office Occupancy	30 (with Owners and Employees)
Stories	Ground Floor, First Floor and Second Floor with Terrace
Total Area	1026 sq.m
Building Area	544.52 sq.m
Structure	Mixed Type Structure with RCC & Bricks
Building Height	10.5 m
HVAC System	Split AC + Mechanical ventilation system without heat recovery
Lighting System	All are LED Lights

Based on architectural drawings and specifications, the original design was simulated using the program Design Builder to investigate the energy efficiency Figure 6. The typical floor plan of the ground floor, first floor, second floor with terrace and 3d model for the prototype are as seen in Figures 6a and 6b respectively.

Figure 6a Typical floor plan for the case study building

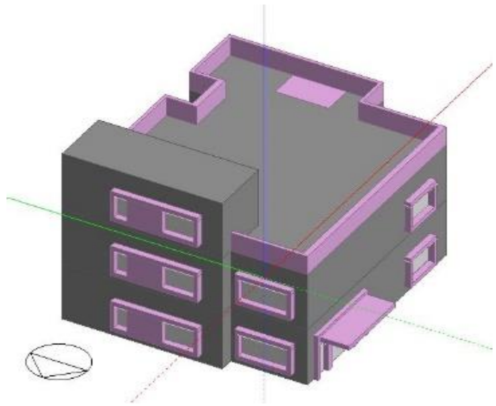

Figure 6b 3d model for the case study building

3.3 *Building data analysis*

The most important data to be considered in this case is the energy consumption data because it has a direct impact on the amount of energy to be saved either through retrofit or to be generated by the renewable energy system. The electricity consumption data form Torrent Power, Ahmedabad, Gujarat, India is used**,** an average consumption monthly rates were detected as seen in Figure 7 from the actual electricity bills of the case study building.

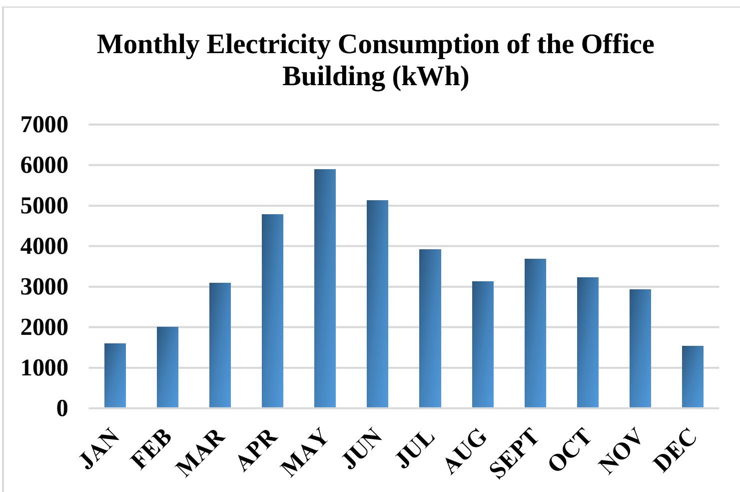

Figure 7 Monthly electricity consumption of the case study office building – 2018

3.3 *The initial condition of the Building*

The case study has been analyzed via computer software tools (Design Builder) according to its original orientation and weather conditions.

By analyzing the data provided in the previous section and through visual investigation, it was found that the building's energy performance can be categorized as poor due to the following:

- The building is only insulated by the traditional thermal insulation on the roof of the top floor as provided by the owner.
- There is traditional shading over the windows to prevent direct sunlight from entering the interior space.
- The windows are single glazed.

- The windows are leaking, so the amount of heat energy transferred from the outside to the inside is significant.
- The HVAC system is a split system not central, and mostly in a moderate condition.

Cross-section view of wall, roof and window with overhang and internal blinds as shown in Figure 8a, Figure 8b and Figure8c.

Figure 8a Cross-section view of the

Figure 8b Cross-section view of roof

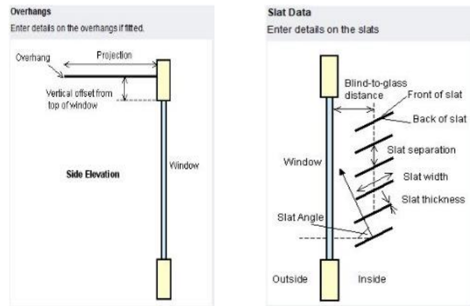

Figure 8c Cross-section view of a window with overhangs and internal blinds

The electricity consumption data form simulation in design builder software. The energy consumption is approximately 24,113 kWh (45 kWh/m^2) for cooling, 11,439 kWh (21 kWh/m^2) for auxiliary, for lighting and computers & equipment is 4,413 kWh (8 kWh/m^2) and 3,357 kWh (6 kWh/m^2) and for miscellaneous is 167 kWh (0.31 kWh/m^2) respectively as shown in Figure 9.

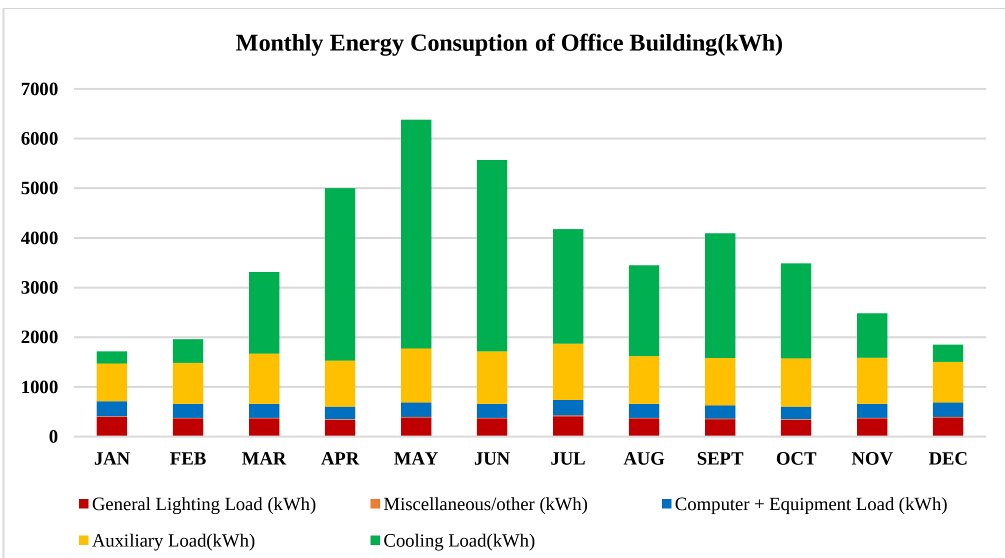

Figure 9 Energy simulation data of original office building

4. Building Components

4.1 Wall

Walls constitute a major part of the building envelope and receive a large amount of direct solar radiation. The resistance to heat flow through the exposed walls may be increased by increasing the thickness (thermal mass), through the cavity wall, by the use of insulating material or by applying light-colored whitewash or distemper on the exposed side of the wall. As per Energy Conservation Building Code (ECBC), recommended U Value wall assembly for 24-hour use building and for daytime use building are given in Table 3.[4]

Table 3 Opaque Wall Assembly U-Factor and Insulation R-value Requirements

Climate Zone	**Hospitals, call centres (24-hours)**		**Other Buildings (Daytime)**	
	Maximum U-factor of the overall assembly (W/m2*K)	**Minimum R-factor of the overall assembly (m2*k/W)**	**Maximum U-factor of the overall assembly (W/m2*K)**	**Minimum R-factor of the overall assembly (m2*k/W)**
Composite	U-0.440	R-2.10	U-0.440	R-2.10
Hot and Dry	U-0.440	R-2.10	U-0.440	R-2.10
Warm and Humid	U-0.440	R-2.10	U-0.440	R-2.10
Moderate	U-0.440	R-2.10	U-0.440	R-2.10
Cold	U-0.369	R-2.10	U-0.352	R-2.35

4.2 Roof

The roof of a building receives a significant amount of solar radiation. Thus, its design and construction play an important role. The heat gain through roofs may be reduced by the use of insulating materials may be applied externally or internally to the roofs. According to ECBC the recommended U-value of roof assembly should be 0.261 and the R-value 2.10 for 24-hour use building and 0.409 and the R-value 2.10 for daytime use building, recommended roof Assembly U-Factor and Insulation R-value Requirements for 24-hour use building and for daytime use building are given in Table 4.[4]

Table 4 Roof Assembly U-Factor and Insulation R-value Requirements

Climate Zone	**Hospitals, call centres (24-hours)**		**Other Buildings (Daytime)**	
	Maximum U-factor of the overall assembly (W/m2*K)	**Minimum R-factor of the overall assembly (m2*k/W)**	**Maximum U-factor of the overall assembly (W/m2*K)**	**Minimum R-factor of the overall assembly (m2*k/W)**
Composite	U-0.261	R-3.5	U-0.409	R-2.10
Hot and Dry	U-0.261	R-3.5	U-0.409	R-2.10
Warm and Humid	U-0.261	R-3.5	U-0.409	R-2.10
Moderate	U-0.409	R-3.5	U-0.409	R-2.10
Cold	U-0.261	R-3.5	U-0.409	R-2.10

4.3 Vertical Fenestration

Fenestration includes products with glass or other transparent or translucent materials. Fenestration, Vertical: Windows that are fixed or movable, opaque doors, glazed doors, glazed block, and combination opaque and glazed doors installed in a wall. In ECBC there are some criteria like:

- Maximum allowable Window Wall Ratio (WWR) is 40%.
- Minimum allowable Visual Light Transmittance (VLT) is 0.27.
- Assembly U-factor includes both frame and glass area weighted U-factors.
- Assembly SHGC includes both frame and glass area weighted SHGC (Solar Heat Gain Coefficient)

as per ECBC the recommended U-factor and SHGC requirements shown in Table 5.[4]

Table 5 Vertical Fenestration Assembly U-factor and SHGC Requirements for ECBC

	Composite	Hot and dry	Warm and humid	Temperate	Cold
Maximum U-factor(w/m²·k)	3.00	3.00	3.00	3.00	3.00
Maximum SHGC Non-North	0.27	0.27	0.27	0.27	0.62
Maximum SHGC North for latitude>15ºN	0.50	0.50	0.50	0.50	0.62
Maximum SHGC North for latitude< 15ºN	0.27	0.27	0.27	0.27	0.62

4. Case Study Simulation: Findings and Analysis

As it has been stated before in the Methodology section, the case study has been analyzed via computer software tools (Design Builder) according to its original orientation and weather conditions. By entering the building envelope parameters and material specifications and glazing transparency, the program can analyze the inputs and provide accurate data on an annual basis which helps to evaluate different passive design elements that influence the energy efficiency of the building. The results show more U-factor and R-factor in wall, roof and windows shows a high above that required, as seen in Figure 10a, Figure 10b and Figure 10c.

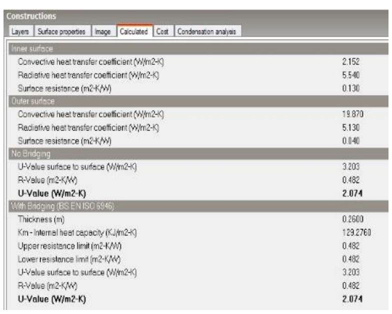

Figure 10a U-value and R-value of wall

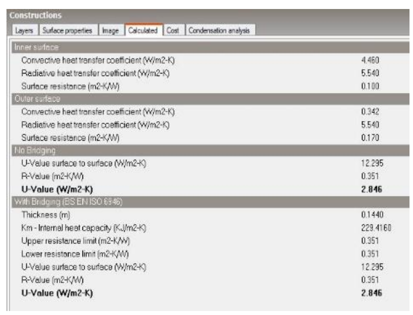

Figure 10b U-value and R-value of Roof

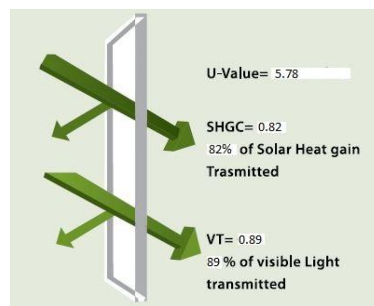

Figure 10c Effect of U-value, SHGC and VT in window

In terms of the interior environment, on an annual basis, Figure 11 shows hourly temperatures which are examined to define the temperature variable between seasons in the interior spaces. These are used to calculate the cooling/heating load demanded that provides thermal comfort for occupants, and determines the total heat gain according to the building construction materials (walls and windows). The results are as follow:

1) From November to March (winter season): the average external temperature is between 21.3 ◦C and 34.9 ◦ C.
2) From April to October (summer season): the average of external temperature increases to between 31.1 ◦C and 41.1 ◦C.
3) From November to March (winter season): the average internal temperature is between 20.7 ◦C and 30.2◦ C.
4) From April to October (summer season): the average of internal temperature increases to between 30.9 ◦C and 41 ◦C.

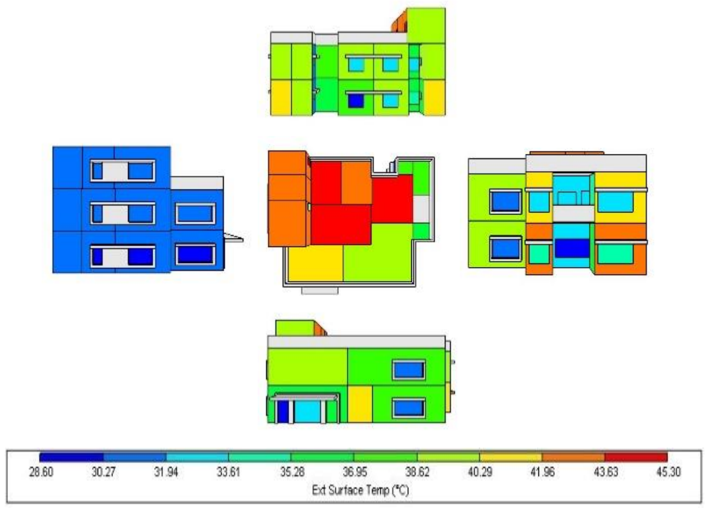

Figure 11a Outside Temperature of the building Including Top, Front, Left, Right and Back View

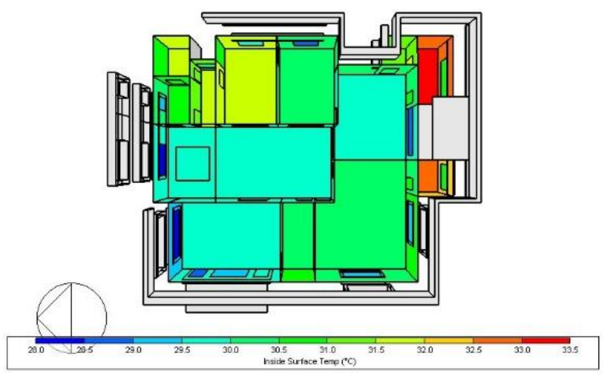

Figure 11b Ground floor Inside Temperature of the building

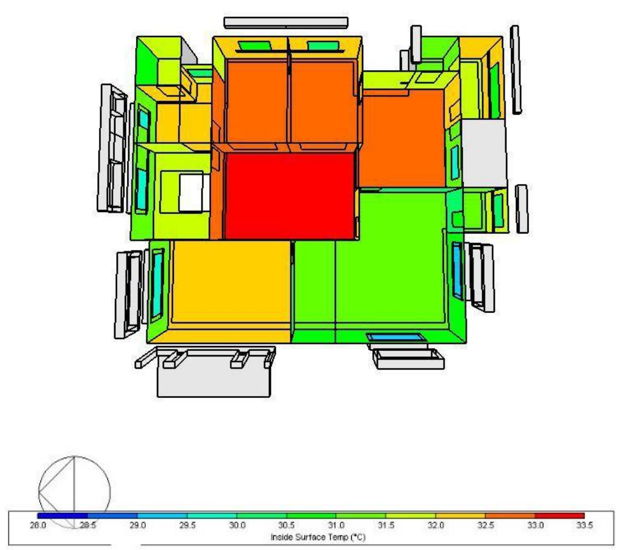

Figure 11c First floor Inside Temperature of the building

5. Scenarios of minimizing the energy consumption of the building

➢ **Scenario-1**

In this scenario, changes in the building envelope were examined. These changes include, firstly, the increase in wall insulation and windows aiming at the reduction of the thermal transmittance between the internal and the external environments, i.e. the U-value, SHGC, VT. The next measure, applied, was the replacement of present windows with more energy-efficient ones with lower U-value, SHGC and VT. These measures are presented in Table 6 and Figure 12.

Table 6 Wall Insulation Assembly

Building Component	Thermal Transmittance/U value (W/m2*K)	Thermal Resistance/R value (m2*k/W)
Wall		
Glassfibre wool(50mm)	**0.534**	**1.871**
1.5cm Cement plaster + 23cm Burned brick + 5cm Glassfibre wool insulation + 1.5cm Cement plaster		

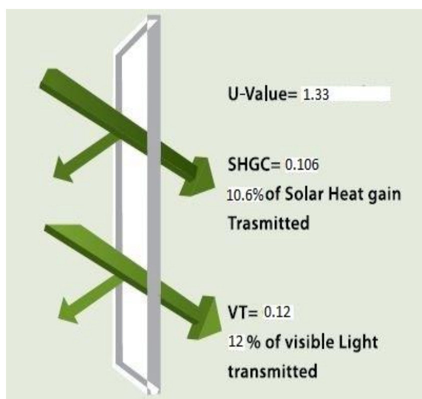

Figure 12 Window Replace into Low Electrochromic Reflected Coloured Double Glazing with Argon Gas (6mm/13mm Argon Gas)

➢ **Scenario-2**

In this scenario, changes in the building Roof. These changes include, firstly, the increase in roof insulation aiming at the reduction of the thermal transmittance between the internal and the external environments, i.e. U-value and R-value. These measures are presented in Table 7.

Table 7 Roof Insulation Assembly

Building Component	Thermal Transmittance/U value (W/m2*K)	Thermal Resistance/R value (m2*k/W)
Roof		
XPS Sheet HFC/CO2 Blowing(70mm)	**0.361**	**2.767**
4cm Concrete Flooring + 7cm XPS Extruded Polystyrene Sheet + 5cm Cement Motar Mix + 12cm RCC with 2% steel + 1.5cm Cement plaster		

➢ **Scenario-3**

In this scenario it was examined how much energy consumption can be achieved by applying measures on building envelopes and internal conditions. Figure 13 describes the combination of Scenario 1 & 2. Form the combination of the scenario 1 & 2 the building energy reduces and the model output is 32265.73 kWh/year shown in Figure 13.

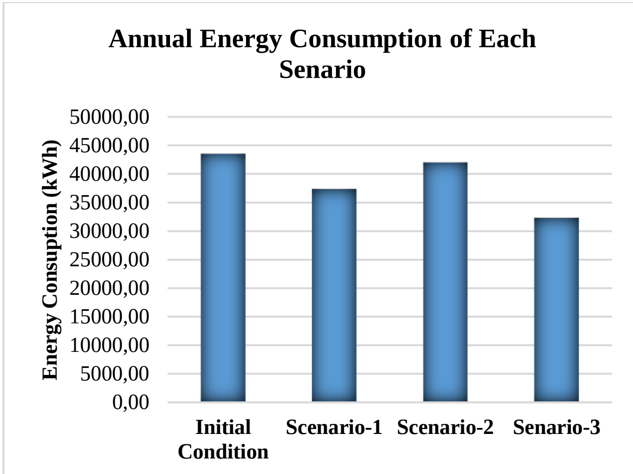

Figure 13 Reduction of energy consumption applying different scenarios

- **Scenario-4**

Average solar irradiation in GUJARAT state is 1,266.52 W/sq.m 1kW solar rooftop plant will generate on an average over the year 5.0 kWh of electricity per day (considering 5.5 sunshine hours). In this case, the building has an accessible working roof area is round about 250sq.m. As per Ministry of New and Renewable Energy in the solar rooftop calculator, 25.0 kW feasible plant size as per site area. Total electricity generation from the solar plant in Annual is 37,500 kWh/year and life of the Photovoltaic panel is 25 years that means solar plant Life-time generation is 9,37,500 kWh (Ministry of New and Renewable Energy).

- **Scenario-5**

From Scenario 3, the reduced energy consumption is 32265.73 kWh/year. The PV panels installed on the rooftop building produce approximately 37500 kWh/year but there is always any system constraints and also the electricity generation is may vary from location condition during on site. So, renewable energy technologies in total produce almost the same quantity of energy consumed.

6. Conclusions

This research investigated how to achieve net-zero energy in existing buildings. And the objective was how commercial buildings in Ahmedabad can reach net-zero energy goals, by taking a commercial two-story building as a research target, the results show an almost 30% reduction in annual energy consumption after applying a combination of scenario to reduce the annual consumption and increase the building energy performance. Most of the energy savings were obtained just through optimizing the existing situation, without replacing or increasing efficiencies.

Focusing only on the energy reduction, by applying energy-efficient measures without considering the cost required, it is the combination of the four energy-efficient scenarios each causing a reduction in the required energy.

Scenario 1, according to which changes on Building Envelope were applied on wall and windows, proved the most energy-efficient among the first four scenarios. The main reason for this effectiveness is because it managed to reduce the cooling needs, which are the main source of consuming energy in the building, by 69%. The less effective scenario proved Scenario 2, as well as, it brought about only a slight reduction in required energy.

In conclusion, the energy-efficient measures with descending efficiency order are the following;

- Increasing the insulation on the walls in Internal and External, improve Thermal Transmittance and Thermal Resistance.
- Replacement of Windows with increasing the airtightness of the building.
- Increasing the insulation on the roof and reducing the heat gain effect on the building.

Concerning the renewable energy, the PV panels produce energy (37,500 kWh/year) it is contributing to achieving NZEB. The PV panels produce the most significant quantity of energy from March to September. Therefore, the energy production derived from renewable energy sources has the same quantity as the energy consumption of the building. Subsequently, by applying the best-case scenario (energy-efficient measures in combination with renewable energy sources), the retrofitting of the present building in order to become an NZEB is achieved.

Acknowledgments

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Forecasting heating degree days for energy demand modeling

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Abstract

Heating degree day (HDD) is a technical index taking into consideration outdoor temperature and average room temperature to describe the need for the heating energy requirements of buildings. HDD can be used to normalize the energy consumption of buildings with respect to heating since the amount of energy needed to heat a building in a given frequency is directly related to the number of heating degree days in that particular frequency. In order to understand the heating demand of the buildings, it is important to investigate the HDD patterns and to construct forecasting models. This study aims at constructing short-term forecast models by analysing the patterns of the HDD. Within this context, time series analysis was conducted by the monthly HDD data in France between 1974 and 2017. The performance of the models were assessed by the adjusted R^2 value, residual sum of squares, the Akaike Information Criteria (AIC) and the Schwarz Information Criteria (SIC) as well as the analysis of the residuals. As a result, the most suitable model was determined as SARIMA $(2,0,1)(1,0,1)_{12}$. The results of the study show that there is a potential to integrate time series models of HDD for short term load forecasting.

Keywords: Heating degree days; short term forecasting; time series;Box-Jenkins method;SARIMA models

1. Introduction

Today, buildings have become the main consumers of world energy use [1]. It is stated that 50% of the energy is spent for heating and cooling in buildings and industry [2]. Moreover, heating and hot water alone constitute 79% of total final energy use in the EU households [2]. The heating demand is affected by several factors such as the building shell, the type of heating system, outdoor temperature, and occupant behaviour. Among all factors, outdoor temperature is the only one directly affected by the climate change. In order to understand variations in the demand for energy required to heat a building due to climate change, a technical index, called as Heating Degree Days (HDD) based on outdoor temperature and average room temperature has been developed [3]. HDD can be used to normalize the energy consumption of buildings with respect to heating since the amount of energy needed to heat a building in a given frequency is directly related to the number of heating degree days in that particular frequency. It is indicated that HDD is a more reliable measure of climatic impact on energy consumption than temperature alone [4]. Therefore, it is important to investigate the HDD patterns to understand the heating demand of the buildings. Accordingly, HDD was integrated in the building energy demand models to improve the prediction accuracy [5–7]. D'Amico et al. [8] identified the relationship between HDD and heating energy performance. Fan et al. [9] estimated the impacts of climatic factors including HDD and Cooling Degree Day (CDD) on electricity demand in China. Kurekci [10] investigated the optimum insulation thickness for building walls by using HDD and CDD values of Turkey's provincial

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centers. Kohler et al. [11] developed a new degree-day method that provides accurate estimates of annual building energy demand for space heating. It should be noted that the performance of the models might be affected by the selection of HDD data. Elizbarashvili et al. [12] estimated daily, monthly and annual HDD and CDD for fourteen different sites of Georgia based on daily mean air temperature data for 30-year period (1961–1990). The results show that there are significant differences for HDD and CDD among the fourteen examined cities of Georgia. OrtizBeviá et al. [13] estimate trends and inter-annual variability in the evolution of HDD and CDD in Spain from observations at 31 stations for an extended period of 1958–2005. The results show that there is a trend which is found to be statistically significant at roughly 2/3 of the Spanish stations used in the study. Although, OrtizBeviá et al. [13] conclude that these trends are similar to those obtained from observations in other parts of Europe, France is stated to be the most temperature sensitive country in Europe [14]. This paper aims at constructing short-term forecast models by analysing the patterns of the HDD. Within this context, time series analysis was conducted by the monthly HDD data in France. The following sections of the paper describe datasets and methodology. Then, findings and conclusions are presented.

2. Dataset and methodology

2.1. Dataset

In this study, the monthly HDD data in France were obtained from the official website of the Statistical Office of the European Union [15]. A total of 528 data covering the period of January 1974 and December 2017 was used to develop the forecasting model. The unit of data is °C * day. Table 1 presents a part of the HDD data used in the analysis.

Table 1. A part of the HDD data from 1974 to 2017.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1974	434.2	385.8	327.9	248.8	128.5	24.71	4.658	2.940	30.13	150.3	297.2	398.4
1975	368.1	345.4	386.7	270.5	186.6	77.73	17.10	11.21	40.27	215.6	331.3	469.7
2015	414.6	402.0	320.5	200.5	117.4	31.28	9.428	8.295	77.75	184.5	222.4	279.9
2016	363.3	341.3	347.9	254.1	135.3	41.40	12.62	8.048	21.08	180.9	289.1	390.3
2017	486.8	321.9	256.0	236.1	109.4	24.20	6.902	10.01	71.63	113.2	300.3	400.1

2.2. Methodology

Box-Jenkins method, also known as the autoregressive integrated moving average (ARIMA) model, was used for time-based analysis and time-based modeling of HDD data. This method applies the autoregressive moving average (ARMA) or ARIMA models to find the best fit of a time series model to the historical values of a time series [16,17]. The seasonal autoregressive integrated moving average model (SARIMA) is an expanded form of ARIMA. SARIMA processes are designed to model trends, seasonal patterns and correlated time series, and have proven to be successful in estimating short-term fluctuations [16,18]. The SARIMA model consists of (1) automatic regression, (2) difference and (3) moving average. SARIMA model is represented as SARIMA (p, d, q) $(P, D, Q)_S$ in which p, d, q represent the degree of non-seasonal linear autoregressive model (AR), non-seasonal difference and degree of non-seasonal moving average model (MA), respectively whereas P, D, Q represent the degree of seasonal AR, seasonal difference and the degree of seasonal MA. In addition, the seasonality length is represented by S. The d and D parameters are taken into account when the series is not stationary.

In this study, to select the most appropriate SARIMA (p, d, q) $(P, D, Q)_S$ model for HDD series, the significance of the coefficients of the models was checked by the Ljung-Box-Pierce Chi-square statistics and t-test. In addition, the corrected R^2 values, the sum of the squares of the residuals, the Akaike Information Criteria (AIC) and the Schwarz Information Criteria (SIC) were taken into account. Furthermore, the residuals analysis including the autocorrelation function (ACF) and the partial autocorrelation function (PACF) of the residuals were conducted. Minitab 18.0 and EViews 10.0 packet programs were used to calculate all the statistics and the model selection criteria.

3. Findings

Fig. 1 shows the plot of time series graph to evaluate the overall behaviour of the HDD series over time. Fig. 1 indicates that the HDD series shows similar periodic fluctuations per month which specifies that the series has a seasonal effect, in other words, it has a seasonality characteristic. Therefore, it can be concluded that the series is not stable.

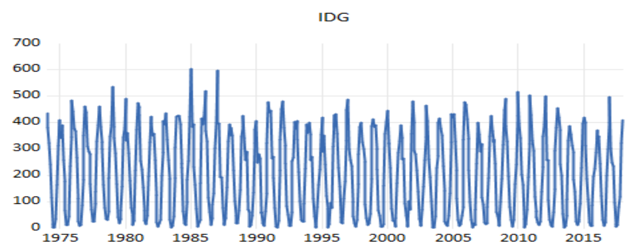
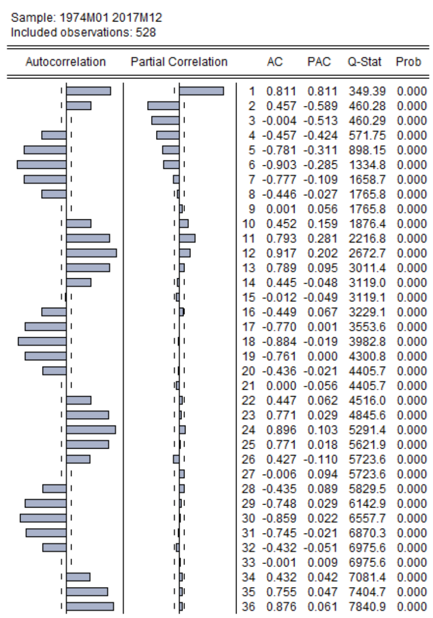


Fig 1. Time series graph of HHD series.

In addition to time series graph, the correlogram of the series was plotted for the k=36 month delay (Fig. 2). This correlogram was created in EViews in order to examine the seasonality.



Sample: 1974M01 2017M12
Included observations: 528

Autocorrelation	Partial Correlation		AC	PAC	Q-Stat	Prob
		1	0.811	0.811	349.39	0.000
		2	0.457	-0.589	460.28	0.000
		3	-0.004	-0.513	460.29	0.000
		4	-0.457	-0.424	571.75	0.000
		5	-0.781	-0.311	898.15	0.000
		6	-0.903	-0.285	1334.8	0.000
		7	-0.777	-0.109	1658.7	0.000
		8	-0.446	-0.027	1765.8	0.000
		9	0.001	0.056	1765.8	0.000
		10	0.452	0.159	1876.4	0.000
		11	0.793	0.281	2216.8	0.000
		12	0.917	0.202	2672.7	0.000
		13	0.789	0.095	3011.4	0.000
		14	0.445	-0.048	3119.0	0.000
		15	-0.012	-0.049	3119.1	0.000
		16	-0.449	0.067	3229.1	0.000
		17	-0.770	0.001	3553.6	0.000
		18	-0.884	-0.019	3982.8	0.000
		19	-0.761	0.000	4300.8	0.000
		20	-0.436	-0.021	4405.7	0.000
		21	0.000	-0.056	4405.7	0.000
		22	0.447	0.062	4516.0	0.000
		23	0.771	0.029	4845.6	0.000
		24	0.896	0.103	5291.4	0.000
		25	0.771	0.018	5621.9	0.000
		26	0.427	-0.110	5723.6	0.000
		27	-0.006	0.094	5723.6	0.000
		28	-0.435	0.089	5829.5	0.000
		29	-0.748	0.029	6142.9	0.000
		30	-0.859	0.022	6557.7	0.000
		31	-0.745	-0.021	6870.3	0.000
		32	-0.432	-0.051	6975.6	0.000
		33	-0.001	0.009	6975.6	0.000
		34	0.432	0.042	7081.4	0.000
		35	0.755	0.047	7404.7	0.000
		36	0.876	0.061	7840.9	0.000

Fig. 2. The correlogram of the HDD series for k=36 month delay.

When the correlogram of the series (Fig. 2) is examined, it is seen that the seasonality shows a structure similar to each other in terms of 12 month delays. In other words, there is a strong association between seasonal neighboring observations. For example, ACF (1), ACF (13) and ACF (25) show similar positive autocorrelations which are statistically significant ($p=0.000<0.05$). In addition, for the delays defined by ACF (3), ACF (15) and ACF (27), the autocorrelations are zero. As a result, it can be confirmed from Fig. 2 that these autocorrelation structures continue systematically and regularly in other delays. Therefore, in addition to the time series graph, the correlogram shows that there is a high association between seasonal observations of the series and that the series is not stationary.

In this study, a total of 79 tentative models were generated. Table 2 presents the 44 of these models. It should be noted that the 44 tentative models shown in the table were generated without constant. Tentative models other than those with a star are also tested by including constant.

Table 2. Tentative models generated in this study.

Models			
*SARIMA $(1,0,1)(1,0,1)_{12}$	SARIMA $(1,0,0)(1,1,1)_{12}$	SARIMA $(1,1,1)(1,1,0)_{12}$	*SARIMA $(1,0,2)(0,1,1)_{12}$
SARIMA $(0,0,1)(1,0,1)_{12}$	*SARIMA $(1,0,1)(0,1,1)_{12}$	SARIMA $(0,1,0)(1,1,1)_{12}$	SARIMA $(1,0,1)(0,1,2)_{12}$
SARIMA $(1,0,0)(1,0,1)_{12}$	SARIMA $(1,0,1)(1,1,0)_{12}$	SARIMA $(1,1,0)(1,1,0)_{12}$	*SARIMA $(0,0,2)(0,1,1)_{12}$
SARIMA $(1,0,1)(0,0,1)_{12}$	SARIMA $(1,0,0)(1,1,0)_{12}$	SARIMA $(0,1,1)(1,1,0)_{12}$	SARIMA $(0,0,1)(0,1,2)_{12}$
SARIMA $(1,0,1)(1,0,0)_{12}$	SARIMA $(0,0,1)(1,1,0)_{12}$	*SARIMA $(0,1,1)(0,1,1)_{12}$	SARIMA $(2,0,0)(0,1,1)_{12}$
SARIMA $(1,0,0)(1,0,0)_{12}$	*SARIMA $(0,0,1)(0,1,1)_{12}$	SARIMA $(1,1,0)(0,1,1)_{12}$	SARIMA $(1,0,0)(0,1,2)_{12}$
SARIMA $(0,0,1)(1,0,0)_{12}$	*SARIMA $(1,0,0)(0,1,1)_{12}$	*SARIMA $(2,0,1)(1,0,1)_{12}$	SARIMA $(2,1,1)(0,1,1)_{12}$
SARIMA $(1,0,0)(0,0,1)_{12}$	SARIMA $(1,1,1)(1,1,1)_{12}$	SARIMA $(1,0,2)(1,0,1)_{12}$	SARIMA $(1,1,2)(0,1,1)_{12}$
SARIMA $(0,0,1)(0,0,1)_{12}$	SARIMA $(0,1,1)(1,1,1)_{12}$	SARIMA $(1,0,1)(2,0,1)_{12}$	SARIMA $(1,1,1)(0,1,2)_{12}$
SARIMA $(1,0,1)(1,1,1)_{12}$	SARIMA $(1,1,0)(1,1,1)_{12}$	SARIMA $(1,0,1)(1,0,2)_{12}$	SARIMA $(0,1,2)(0,1,1)_{12}$
SARIMA $(0,0,1)(1,1,1)_{12}$	*SARIMA $(1,1,1)(0,1,1)_{12}$	SARIMA $(2,0,1)(0,1,1)_{12}$	SARIMA $(0,1,1)(0,1,2)_{12}$

As the first step, the models which comply with both of the following conditions were selected: (1) the models with correlations that are statistically significant; (2) the models with the chi-square statistics of the residuals of k=12,24,36 months delay are statistically insignificant, in other words, the residuals of the models are not correlated with each other. As a result, 9 models were selected for further analysis. In the next step, the adjusted R^2 value, the residual sum of squares, the AIC and the SIC were calculated to select the appropriate model. The selected models and the selection criteria values are presented in Table 3.

Table 3. The selected models in the first step and second step selection criteria.

	Model	Adjusted R^2	Residual sum of squares	AIC	SIC
1	SARIMA $(1,0,1)(1,0,1)_{12}$	0.936654	828032.9	10.33716	10.37759
2	SARIMA $(1,0,1)(0,1,1)_{12}$	0.475825	812361.4	10.26529	10.29820
3	SARIMA $(0,0,1)(0,1,1)_{12}$	0.464422	831655.0	10.27557	10.30026
4	SARIMA $(1,0,0)(0,1,1)_{12}$	0.615053	1090103.0	10.57437	10.59910
5	SARIMA $(1,1,1)(0,1,1)_{12}$	0.721348	787551.5	10.27085	10.30382
6	SARIMA $(0,1,1)(0,1,1)_{12}$	0.715896	804533.5	10.28096	10.30569
7	SARIMA $(2,0,1)(1,0,1)_{12}$	0.936911	816848.7	10.32561	10.37412
8	SARIMA $(1,0,2)(0,1,1)_{12}$	0.487184	793205.5	10.26017	10.30132
9	SARIMA $(0,0,2)(0,1,1)_{12}$	0.467373	825461.2	10.27325	10.30617

Regarding the selection of the most appropriate forecasting model among the models selected in the first step, the criteria shown in Table 5 were taken into account. The higher the model's adjusted R^2 value, the lower the residual sum of squares, the lower the AIC and the SIC are, the better the model is. Accordingly, the model that addresses most of the criteria at the same time is selected. Table 3 shows that the adjusted R^2 value of the models vary between 0.464422 and 0.936911 and the highest values are observed in the 1st and the 7th models. Then, the residuals sum of squares, AIC and SIC values of these models were compared. The values of the aforementioned criteria for the 7th model are smaller than those of the 1st model. As a result, the 7th model, namely SARIMA $(2,0,1)(1,0,1)_{12}$, was selected as the suitable and the final forecasting model. However, it should be noted that the graph of the residuals should be examined to check the appropriateness of the final forecasting model. The graphs obtained via Minitab are presented in Fig. 3.

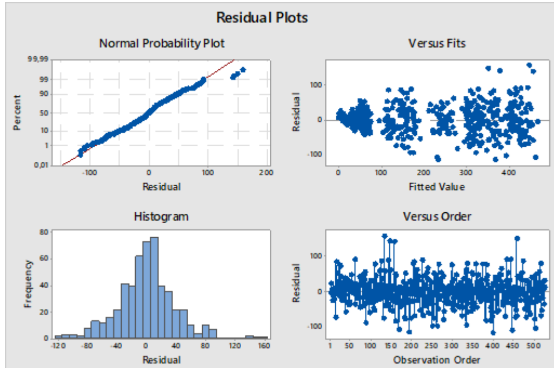


Fig.3. Plots of the HDD series' residuals according to the selected model.

It should be noted that the residuals should be normally distributed with zero mean and constant variance. The normal probability plot and histogram in Fig. 5 shows that residuals except for the last residuals approximately suit to normal distribution. In addition, versus fits graph shows that the variance tends to increase slightly. It should be noted that this situation can be caused by the large variation of the data in the series. In addition to the plots in Figure 3, ACF and PACF plots of the residuals, which are the most examined plots in the model selection, are presented in Fig. 4 and Fig. 5.

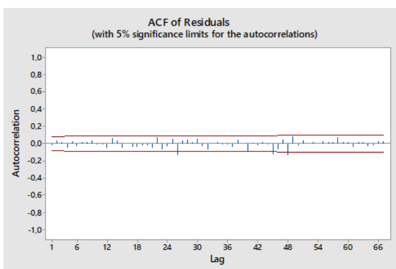


Fig.4. ACF plot of residuals.

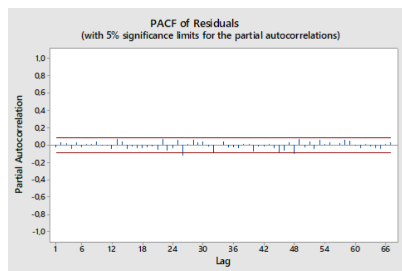


Fig. 5. PACF plot of residuals.

The plots indicate that most of the autocorrelations of the residuals are zero, in other words, they are not correlated. Thus, it can be concluded that the chosen model is appropriate.

The monthly actual HDD values as well as the monthly forecasted HDD values and the confidence intervals obtained via the SARIMA (2,0,1) $(1,0,1)_{12}$ model are shown in Fig. 6. The plot shows that the forecasted HDD values are close to the actual HDD values. In addition, the actual and forecasted HDD values of 2017 are presented in Table 4 which also indicates that the forecasted HDD values are close to the actual HDD values.

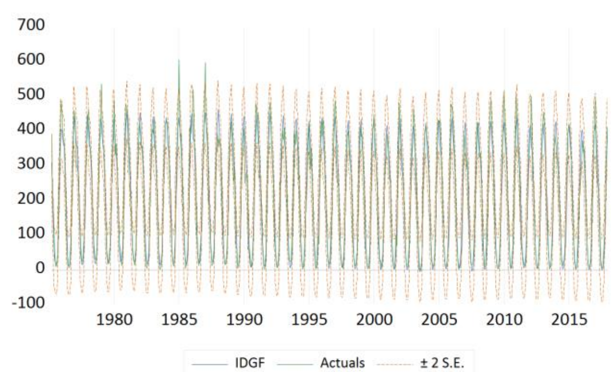


Fig. 6 The actual values, the forecasted values and the confidence intervals of the HDD data according to model SARIMA (2,0,1) $(1,0,1)_{12}$.

Table 4. The actual and forecasted HDD values for 2017

Months	Actual (kWh)	Forecasted (kWh)
2017M01	497.52	417.986
2017M02	303.62	361.840
2017M03	248.77	308.607
2017M04	233.89	217.635
2017M05	95,36	111,711
2017M06	14,73	32,316
2017M07	4,98	4,335
2017M08	10,36	5,148
2017M09	78,48	48,420
2017M010	117,86	151,317
2017M011	321,16	294,122
2017M012	411,22	395,733

4. Conclusion

In this study, time series analysis was conducted by the monthly HDD data in France between 1974 and 2017. Seventy nine SARIMA models were constructed and the models were evaluated according to the adjusted R^2 value, residual sum of squares, AIC and SIC criteria as well as the analysis of the residuals. SARIMA $(2,0,1)(1,0,1)_{12}$ model was selected as the final forecasting model. The results show that the SARIMA models yield fairly acceptable forecasts for supporting short-term forecasting of HDD. Future studies can focus on the integration of these models in the forecasting models of the heating demand in buildings.

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Measures to regain productivity after construction accidents

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Abstract

When construction accidents occur, besides the direct impact on the victims, there may be collateral effects on the remaining/uninjured workers. In the context of the aftermath of accidents on construction sites, this research investigates the extent to which the uninjured workers' productivity is affected; and uncovers the more effective measures to be instituted on workers after witnessing construction accidents so as to prevent further loss of their productivity. A questionnaire survey was conducted on randomly selected construction professionals who had been supervising workers when and after accidents took place on construction sites in Singapore. The data collected were analyzed using the SPSS software. The first finding is that workers' productivity and wellbeing fall significantly after witnessing construction accidents. They have lower morale, are distressed by the accident and stressed by having to take on additional work or accelerate their work after construction resumes on site. This research found that while a worker's wellbeing deteriorates significantly in the aftermath of a construction accident, there are upsides to construction accidents too. Workers are observed to adopt better work attitude and have higher sense of safety after construction accidents. Significant positive correlation is found between workers' wellbeing and their productivity. The second finding is that the workers turn to fellow workers and supervisors for support post accidents. Relieving them from duties are also effective measures to alleviate the psychological effects of the accidents. The study found that to minimize the negative effects of construction accidents, contractors should improve site safety swiftly, offer employee assistance program, relieve workers from regular duties temporarily and refrain from overloading them after work is allowed to resume. It is recommended that supervisors avail themselves to the workers, for example, through mass psychological debriefing or one-to-one counselling.

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Keywords: accidents; morale; productivity; safety; wellbeing

1. Introduction

Safety in the construction industry is important as the work environment is prone to accidents [1]. This is especially essential to not only ensure a safe environment for all, but also enable work to be carried out productively [2]. Construction accidents would delay the project [3] and increase project cost [4]. Serious construction accidents also have a negative impact on employees, including physical and psychological effects [5]. Accidents may bring about stress to the workers who witnessed the accident, and wellbeing could be affected [6]. However, there is a lack of research on how accidents affect the wellbeing of workers and the association between workers' wellbeing and workers' productivity.

The aim of the study is to understand the state and association of workers' wellbeing and productivity after witnessing

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accidents on site. In the context of the aftermath of accidents on construction sites, the specific objectives are to: investigate the extent to which workers' productivity is affected; examine the state of workers' wellbeing; investigate the association between workers' wellbeing and productivity; and explore the ways in which workers' wellbeing could be enhanced so as to prevent further loss of their productivity.

The scope of this study is limited to construction workers, and their wellbeing and productivity which were observed by their supervisors after reportable injuries/accidents happen on construction projects in Singapore. The reportable injuries are categorized by the Singapore Ministry of Manpower as follows [7]: minor injuries (reportable injuries that did not result in death or major injuries); major injuries (non-fatal injuries, but are more severe in nature); and fatal injuries.

2. Brief literature review

Construction accidents have several consequences. The obvious one is the physical injury to the individual or victim. Accidents also have social and financial impacts [8]. The social impacts of site accidents are defined as the effect that would touch the human side; affecting the people revolving around it [8]. The financial impact include direct and indirect costs.

Direct costs arise clearly from the accidents and include medical expenses, compensations and legal costs, while indirect costs are those attributed to lost productivity, time and lower morale [5, 7]. An accident can cause a direct loss of production and also wider disruptions in the production process [9], thereby affecting productivity [10].

Workers' wellbeing can be affected by both distress and morale [11]. Distress comes from stressors at work and workers under distress may feel anxious, guilty and sad [11]. The damage to morale has a significant effect on a company's performance [12]. Feeling physically safe is an important factor contributing to morale at work [13]. People working in the construction industry have a high risk of developing post-traumatic stress disorder (PTSD) because unexpected and extreme accidents may happen [14].

The literature review showed that witnessing accidents affect workers' wellbeing. Furthermore, it is known that accidents affect workers' productivity. However, the gap in knowledge is that the link between workers' wellbeing and productivity after witnessing construction accidents is hitherto not known. The extent to which a worker's wellbeing deteriorates after witnessing a construction accident is also not known. The fieldwork is therefore constructed to fill the knowledge gap.

3. Research method

The research design is a survey, and data were collected using a specially designed questionnaire. The Y variable is the extent to which workers' productivity is affected in the aftermath of an accident on site, measured on a 5-point Likert scale (1=affects very negatively; 5=affects very positively). The X variables are the extent to specific things/attitudes change after an accident on site, measured on a 5-point Likert scale (1=change very negatively; 5=change very positively). The target population was all construction professionals who had been supervising workers on site at the time and after a construction accident took place. The samples were randomly selected from names listed on Singapore Contractors Association Ltd and Workplace Safety and Health Council's websites. Data was collected via an online survey and analysed using the Statistical Package for Social Sciences (IBM SPSS Statistics 24) software.

4. Characteristics of sample

500 emails inviting participation in the survey were sent out and 40 usable responses were collected, giving a response rate of 8%. The characteristics of the respondents are shown in Table 1. The majority of the respondents are male (85%). More than half (52.5%) of the respondents are contractors (main and subcontractors). Many of them (67.5%) are in management positions. The majority have more than 10 years of experience in the industry (82.5%). The range is 3 to 47 years with a mean of 20.7 years. Most of them have experience in leadership for more than 10 years (65%).

The average years of experience as a leader is 15.1 years. 62.5% of them are site supervisors, project managers and safety managers who worked closely with workers on site at the time of the accident. The respondents are well placed to inform the research as they had relatively long experience in the industry and as leaders. The findings are more representative of contractors.

Table 1. Profile of Respondents

Description	Frequency	%
Gender		
Female	6	15
Male	34	85
Main Business		
Developer	2	5
Consultant	7	17.5
Main Contractor	18	45
Subcontractor	3	7.5
PM Company	10	25
Designation		
Professional	13	32.5
Mid Management	18	45
Senior Management	9	22.5
Experience in Industry		
3-10 years	7	17.5
11-20 years	14	35
21-30 years	16	40
> 30 years	3	7.5
Experience as Leader		
< 3 years	1	2.5
3-10 years	13	32.5
11-20 years	17	42.5
21-30 years	9	22.5

5. Results and discussion

Objective 1 is to investigate the extent to which workers' productivity is affected in the aftermath of an accident on site (Y). The results in Table 2 show that for minor accidents (Y_a), workers' productivity is not affected significantly (mean Y_a= 2.93, p= 0.131). For major accidents (Y_b= 2.65, p=0.004) and fatal accidents (Y_c= 2.60, p= 0.031), workers' productivity levels drop significantly. The findings suggest that as the severity of accidents increases, there is greater productivity loss.

Table 2. Results of One-sample T-test

Code	Variable description	Mean	t	Sig. (1-tail)
Y_a	The extent to which workers' productivity is affected in the aftermath of an accident on site	2.93	-1.138	0.131
Y_b		2.65	-2.759	0.004**
Y_c		2.60	-1.922	0.031*
$X1_a$	The extent to which workers' work attitude changes after a construction accident	3.20	2.082	0.022*
$X1_b$		3.48	2.276	0.014*
$X1_c$		3.60	2.306	0.013*

Code	Variable description	Mean	t	Sig. (1-tail)
$X2_a$	The extent to which worker's psychological health changes after a construction accident	3.00	0.000	0.500
$X2_b$		2.85	-0.771	0.223
$X2_c$		2.90	-0.392	0.349
$X3_a$	The extent of workers' distress after a construction accident. (eg. anxiety, pain, or sorrow)	4.20	-6.150	0.000**
$X3_b$		3.10	-12.577	0.000**
$X3_c$		2.23	-14.521	0.000**
$X4_a$	Workers' sense of safety level of the workplace after a construction accident	3.18	1.862	0.035*
$X4_b$		3.73	4.223	0.000**
$X4_c$		4.08	5.276	0.000**
$X5_a$	The extent to which workers' stress level is affected when they undertake additional work after a construction accident	2.90	-2.082	0.022*
$X5_b$		2.63	-3.204	0.001**
$X5_c$		2.53	-2.829	0.004**
$X6_a$	The extent to which worker's morale is affected after a construction accident	2.88	-1.706	0.048*
$X6_b$		2.45	-3.731	0.000**
$X6_c$		2.13	-4.242	0.000**

Notes: Subscripts a, b and c refer to minor, major and fatal accidents respectively. * p <0.05; ** p < 0.01.

Objective 2 is to examine workers' wellbeing in the aftermath of an accident on site. Table 2 shows that they become significantly distressed (X3), experience significant stress when having to take on additional work after the accident (X5), and have significantly lower morale (X6). On the positive side, their work attitudes (X1) improve and sense of safety level (X4) increases after accidents.

Objective 3 is to investigate the association between workers' wellbeing and productivity after accidents. Table 3 presents the significant correlations between workers' productivity (Y) and workers' wellbeing variables (X) in the aftermath of an accident on site. The results show a significant positive correlation between workers' attitude (X1) and workers' productivity in the aftermath of an accident on site (Y) for all 3 categories of accidents, suggesting positive changes after workers learn from new experiences.

Table 3. Significant Correlations with Productivity

Variable	Minor accident (Y_a)		Major accident (Y_b)		Fatal accident (Y_c)	
Code	r	Sig	r	Sig	r	Sig
X1	0.567	0.000**	0.403	0.010*	0.540	0.000**
X2	0.616	0.000**	0.595	0.000**	0.825	0.000**
X3	0.419	0.007**	-	-	-	-
X4	0.468	0.002**	-	-	-	-
X5	0.344	0.030*	0.421	0.007**	0.576	0.000**
X6	-	-	0.662	0.000**	0.508	0.001**

* p <0.05; ** p < 0.01.

Table 3 shows a significant positive correlation between workers' psychological health (X2) and workers' productivity (Y) in the aftermath of an accident on site. This suggests that when workers' psychological health deteriorates, productivity loss is likely to take place, regardless of the severity of the accident.

In the aftermath of an accident on site, workers experience significant distress (X3) such as anxiety, pain or sorrow, and their distress worsens as the severity of accidents increases from minor to major to fatal (see Table 2, means $X3_a$=

4.2, $X3_b$= 3.10 and $X3_c$= 2.23). Significant positive correlation is found between distress in workers ($X3_a$) and workers' productivity (Y) when minor accidents happen (see Table 3) suggesting that when workers' distress becomes more serious, workers' productivity is affected negatively.

There is a significant positive correlation between workers' perceptions of workplace safety ($X4_a$) and workers' productivity after minor accidents happen (Y_a) (see Table 3). This may be explained by improvement in site safety after construction accidents happen.

The remaining workers on site may be asked to cover the duties of accident victims. The results show that having to take on additional work increases stress level of these workers, and the stress worsens as the severity of accidents increases (see Table 2, means decrease from 2.90 ($X5_a$) to 2.63 ($X5_b$) to 2.53 ($X5_c$) as accident severity moves from minor to major to fatal). The extent of stress brought about to the remaining workers on site from having to do additional work (X5) is significantly and positively correlated with workers' productivity (Y) for all three categories of accidents (see Table 3).

As the severity of accidents increases, workers' morale is affected more negatively (see Table 2, means decrease from 2.88 ($X6_a$) to 2.45 ($X6_b$) to 2.13 ($X6_c$) as accident severity moves from minor to major to fatal). The morale of workers (X6) is significantly correlated with workers' productivity (Y) in major and fatal accidents (see Table 3).

6. Recommendations

The research asked respondents what actions are taken by workers or their employers after witnessing construction accidents. To seek solace, 95% and 83% turn to peers and supervisors respectively. 40% turn to family members. About 55% of the contractors relieved workers from their duties temporarily and 35% referred workers to professionals to alleviate psychological effects in the aftermath of accidents. The majority of workers were required to cover the duties of victims.

It is recommended that after an accident, contractors should swiftly improve their safety management system. The improved site safety may give workers peace of mind and enable them to work productively. Improving workers' morale (X6) after major and fatal accidents may lead to higher productivity (see Table 3). This suggests that contractors should set aside time for workers to commiserate with each other. Supervisors should avail themselves to listen to the workers after accidents occur. For fatal accidents, it is recommended that contractors offer workers access to counsellors so as to improve their psychological health.

Construction accidents affect workers' psychological health (see X2 in Table 2). It is recommended that workers be relieved from duties, and given time off in order to recover from the psychological shock. It is not recommended that workers who witnessed the accident be asked to over the work of the accident victims immediately as the longer term negative effect of stress and low morale outweigh the need to complete the project in a timely manner.

7. Conclusion

The results show that workers' productivity fall significantly after witnessing major and fatal accidents (see Table 2). Workers' wellbeing is significantly affected after construction accidents. They have lower morale, greater distress and higher stress level (see Table 2). However, there are positive changes to their work attitude and perceptions of workplace safety.

This study contributes to knowledge by showing that there is a significant positive correlation between wellbeing and productivity of workers in the aftermath of construction accidents (see Table 3). As wellbeing deteriorates, productivity also declines. It is recommended that in the aftermath of construction accidents, employers should focus on improving workers' wellbeing as this may bring the productivity up again. It is suggested that workers be offered employee assistance programs to improve their psychological health and morale. Contractors should quickly improve their safety management system on site. They should refrain from assigning workers with additional work which was originally the victims' work or to catch up with the schedule, as these contribute negatively to workers' productivity.

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Safety Culture of the Herbert Hoover Dike Contractors

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Abstract

The construction industry remains one of the most dangerous industries to work in even after decades of safety improvements [1]. Researchers, such as Zohar, have argued that safety climate, or safety culture, is "a robust leading indicator or predictor of safety outcomes across industries and countries" [2]. This study made use of mixed methodology that blends quantitative and qualitative research methods to gauge the relative level of commitment each project's workforce has to a positive safety culture at Herbert Hoover Dike. The quantitative portion of the research revealed a positive perception of safety among craft workers. The qualitative portion of the research revealed major themes and subthemes associated with safety culture on the project. Further research is needed to capture additional workers on this project as well as connect safety culture with accident rate with this and other construction projects.

Keywords: Herbert Hoover; safety; safety culture

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1. Introduction

The construction industry remains one of the most dangerous industries to work in even after decades of safety improvements [1]. While many hazards have been eliminated through legislation and improved safety equipment, unsafe working conditions persists [3]. The safety climate or safety culture of an organization is defined as "product of individual and group values, attitudes, perceptions, competencies, and patterns of behaviour that determine the commitment to, and the style and proficiency of, an organization's health and safety management" [4]. It is the collective values members of an organization share about safety.

Researchers, such as Zohar, have argued that safety climate, or safety culture, is "a robust leading indicator or predictor of safety outcomes across industries and countries" [2]. Published research on worksite safety have argued that it is important to create metrics to measure safety in order to understand whether safety measures actually prevent accidents and illnesses. Measuring performance "1) enables reasoned decisions and assessments, 2) allows comparison with previous (or other's) performance and 3) compares actual performance with planned performances" [5].

The United States Army Corps of Engineers (USACE) relies on lagging indicators to measure safety performance. Lagging, or trailing, indicators are linked to the outcomes of an accident. Lagging indicators include accident reports, OSHA statistics, total recordable index, lost-time index and number of days restricted [6]. Lagging indicators are subject to manipulation by those reporting them. Certain facts may have been omitted, changed, or the incident not reported at all. This research is significant because it provides a snapshot, or baseline, of the safety culture of the contractors performing work at Herbert Hoover Dike (HHD) as measured by leading factors such as confidence in

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management to ensure a safe working environment, self-reported risk taking by the craft workers and work pressure. Existing research suggests that there is no universal metric by which all projects are judged and must be developed for each organization. By creating a baseline through this research, future surveys can be undertaken to measure the positive or negative changes in the safety culture.

2. Research Summary

This study made use of mixed methodology that blends quantitative and qualitative research methods to gauge the relative level of commitment each project's workforce has to a positive safety culture at Herbert Hoover Dike.

2.1 Questionnaires

Questionnaires were selected as the quantitative method of data collection for this research. The questionnaire was developed in English but a Spanish version was developed as a sizeable percentage of the craft workforce at HHD is native Spanish speakers. Survey takers were asked to answer a series of demographics questions concerning gender, age, length of time in the construction industry, role (prime or subcontractor), and management level (management/supervisor, or worker). Survey takers were also asked to rate a series of twenty-seven questions on a Likert scale from 1 to 5, with 1 being that they strongly disagreed with the statement and 5 being they strongly agreed with the statement. These Likert scale questions focused on management, safety systems, risk, work pressure and competence. A copy of the complete questionnaire can be found in Appendix A for reference. The candidate population was the entire contractor craft workforce as the research attempted to understand the safety culture of the Herbert Hoover Dike workforce. The survey attempted to reach the greatest breadth of the craft workforce possible. The population of the entire contractor workforce at HHD varies with time but a reasonable estimate is between 50 and 80 individuals on any given day.

Survey data were analyzed using Microsoft Excel. A baseline response was established for each question by averaging all of the survey responses to that particular question. The data was then sorted into subpopulations based on criteria such as age, experience level, and gender. Then, each criteria was compared to the baseline in order to identify any statistically significant differences in the subpopulation mean results by using t-tests (Farrell, 2011).

2.2 Semi-Structured Interviews

Semi-structured interviews were chosen as the qualitative method for this research. This structure of interview allows for insights into problems or issues that the questionnaire may not have revealed. The semi-structured interviews were administered to no fewer than six and no more than twelve interviewees as research shows this range is sufficient to draw meaning (Guest et al., 2006). Candidates were selected based on convenience sampling and were selected by the researcher for their close, first-hand knowledge of the site conditions at HHD.

Answers to the interview questions were first entered into Microsoft Word and formatted for ease of reading and coding. Personally identifiable information was then removed to ensure the confidentiality of the interviewee. Important phases and sentences were then given a code for the key idea or theme expressed. The codes were analyzed to develop sub-themes and the sub-themes were then in turn analyzed to produce the principle themes. (Saunders et al., 2009).

3. Results and Discussion

3.1 Questionnaires

A total of twenty-seven questionnaires were collected. Table 1 shows the frequency of responses from each demographic group and percentage of responses that that group represents out of the total population.

Table 1. Demographics of Questionnaire Respondents.

Preferred Language	English	Spanish				
	23 (85%)	4 (15%)				
Gender	Male	Female				
	24 (89%)	3 (11%)				
Age (years)	18-20	21-29	30-39	40-49	50-59	60+
	0 (0%)	1 (4%)	7 (26%)	6 (22%)	9 (33%)	4 (15%)
Experience (years)	0-1	2-5	6-10	11-15	16-20	21+
	3 (12%)	4 (15%)	2 (8%)	0 (0%)	5 (19%)	12 (46%)
Employed By	Prime	Subcontractor				
	17 (63%)	10 (37%)				
Management Level	Management	Worker				
	14 (54%)	12 (46%)				

As shown in Table 1, the questionnaire respondents were primarily English speaking (85%), male (89%), most likely to be 30 years or older and have a mixed of experience levels. There was a skew towards being employed by the prime contractor (63%) but this is not unexpected as heavy civil work construction often has a high percentage of self-performed work compare to other construction subsectors. Slightly more than half (54%) identified themselves as some sort of supervisor or manager.

Figure 1 shows the frequency of responses from each of the individual survey questions (in all categories). The responses to the individual safety culture statements are predominately positive with an average response of a 4.09 (Agree), a standard deviation of 1.17 and a mode of 5 (Strongly Agree). In fact, 78% of the responses were positive and only 13% were negative. The remaining 9% were neutral.

The researcher found no significant difference in the mean responses for the English or Spanish subgroups. The researcher also found no significant difference in the mean responses for the Male or Female subgroups These results suggests that language and gender do not have an impact on the perceptions of the safety culture for those surveyed.

Figure 2 shows the frequency of responses by age range. The researcher found no significant difference in the mean responses for the various ranges of age subgroup. This result suggests that age does not have an impact on the perceptions of the safety culture for those surveyed.

The researcher also found no significant difference in the mean responses for the various ranges of experience of each respondent indicating that years of experience does not have an impact on the perceptions of safety culture for those surveyed.

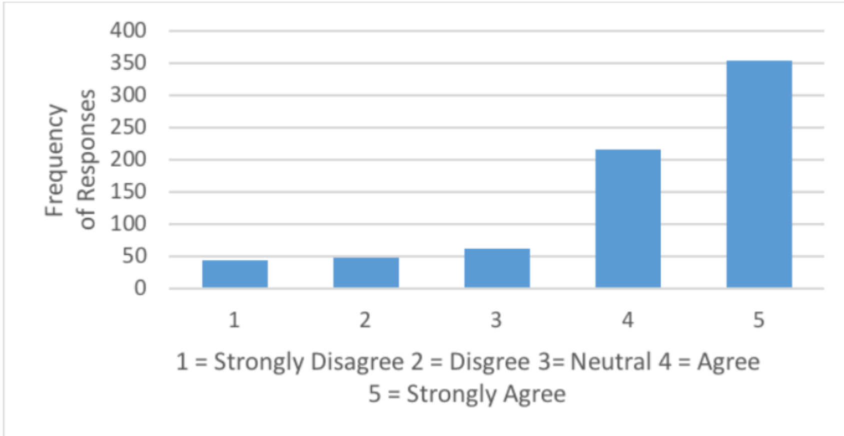

Figure 1: Frequency of Questionnaire Answers

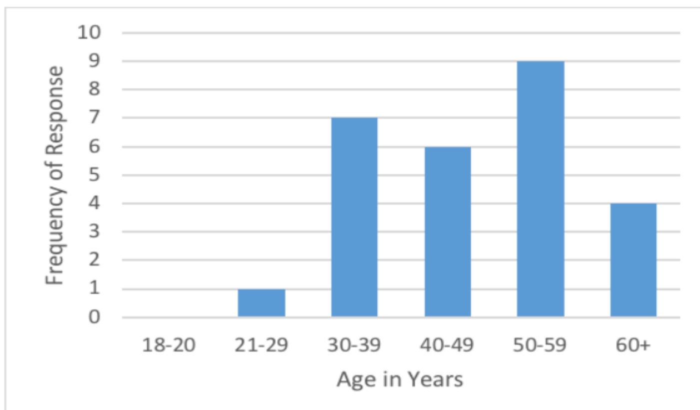

Figure 2: Frequency of Responses by Age

The researcher found no significant difference in the mean responses for the prime contractor or subcontractor subgroups. Nor was there a significant difference between those who identified as management/superintendent or worker. This result suggests that employment with either the prime contractor or subcontractor does not have an impact on the perceptions of the safety culture for those surveyed. The employee's particular role within the company also does not have an impact on perceptions.

3.2 Semi-Structured Interviews

Thematic analysis was performed on the interviews to identify the themes common between the interviewees. The analysis uncovered the following three major themes: (1) Management, (2) Worker and (3) Safety Officer. Each major theme had associated subthemes which are shown in Figure 3.

The management theme includes all of the items that the site management team has control over, the motivations for maintaining site safety, and the situations in which the owner must intervene.

Figure 3: Safety Culture Interview Thematic Analysis

The priority subtheme encompasses the apparent level of concern, or priority, the site management places on safety. One interviewee stated, "*the site management I've been involved with has a positive attitude regarding safety*" and that they "*seem fairly proactive*." The other interviewees noted a similar general positive attitude towards safety. It was also noted in several of the interviews that management seems to prioritize safety hazards by severity. Interviewee 3 stated that *"some [safety] deficiencies take longer"* but *"deficiencies that can pose immediate danger to the employees are addressed almost immediately"*

Owner intervention was another subtheme found within the interviews. This subtheme includes the necessity of owner intervention in the site management's safety efforts. The level of intervention described in the interviews varies from the occasional reminder to demands for the site management to terminate employees. Overall, the theme was that owner intervention is required at some level.

The Compliance subtheme includes the motivations of why the site management maintains an adequate safety program. The conclusion drawn from the statement made by the interviewees is that safety is largely a contractual and legal compliance issue. One interviewee said that site management corrects safety deficiencies because the deficiencies *"threaten[s] to impact work performance"*

The worker theme includes ways in which the worker's attitudes, behaviors and knowledge has an impact on his or her own personal safety.

The experience subtheme encompasses the role in which an individual worker's experience plays in the choices he or she makes on the jobsite. One interviewee discussed how more experienced workers are more safety conscious in this quote: "*older guys who have been around have seen [accidents] happen and know that all it takes is someone not paying attention and they can get hurt."* In a different interview the following quote discusses how inexperienced workers are less safety conscious: *"labor for hire workers…seem to be bothered by some of the basic safety equipment, like properly wearing PPE."*

Training is a common subtheme in the interviews in how it pertains it is important in imparting the skills necessary to the workers to identify hazards on the jobsite. This can be seen in the follow quote: *"Many employees can identify safety hazards but to accomplish this the contractor need to have a good safety program that keeps the employees aware of the risks."*

Shortcut taking was identified by the researcher as another subtheme. This subtheme includes the propensity of otherwise experienced, training, and safety conscious workers to take risks on the jobsite. The interviewees believed most shortcut taking was done out of *"laziness"* or a worker being *"in a hurry"* or overconfidence. Shortcut taking was also noted to be done when a worker's supervisor or the site safety officer was not present.

The safety officer theme includes the role the safety offers plays in administering the safety program and the authority vested in him or her. The safety officer, while not always explicitly named, is a central figured discussed in the interview.

Authority of the safety officer is a subtheme that involves the authority and responsibility delegated to the safety officer on site. The interviewees noted that the safety officer *"have the authority to stop work if there is a safety risk*." One interviewee stated that a crane operator was "suspended for 3 days from the site" for *"disobeying the SO order."* This is evidence of site managements inherit support of the authority of a safety officer.

The communication subtheme outlines how training and information is imparted to the worker through the safety officer. This is accomplished through weekly toolbox meetings, new worker safety indoctrinations and activity hazard analyses.

4. Conclusions and Recommendations

For survey data gathered from craft workers, the responses to the individual *safety culture* statements were predominately positive with an average response of a 4.09 (Agree), a standard deviation of 1.17 and a mode of 5 (Strongly Agree). The researcher found no significant difference in the mean responses for the following subgroups:

- English or Spanish Speaking
- Male or Female
- Age Range
- Years of Experience
- Employed by Prime Contractor or Subcontractor
- Holding a Management/Superintendent or Worker Position

The results indicate that none of the factors listed above have an impact on perceptions of safety culture for those surveyed.

The semi-structured interviews revealed three three major themes: (1) Management, (2) Worker and (3) Safety Officer. Under management, the priority subtheme revealed a positive attitude toward safety from site management. Owner intervention was identified as management subtheme, indicating the perception among interviewees that owner intervention is required for success. For the compliance subtheme, the interviewees revealed the perception that safety is largely a contractual and legal compliance issue.

Under the worker theme, the experience subtheme encompasses the role in which an individual worker's experience plays in the choices he or she makes on the jobsite. The perception was generally that more experience leads to more safety consciousness. Worker training was also identified as an important subtheme in terms of transferring skills necessary to identify jobsite hazards. Interviewees also identified shortcut taking as a worker subtheme, citing many workers taking shortcuts when in a hurry, overconfident, or when the safety officer is not present.

The safety office theme revealed subthemes of authority and communication. Interviewees indicated that safety officers have authority and responsibility to stop work that is unsafe. Communication refers to the transfer of training from the safety officer to workers through meetings and training.

Further research should aim to administer the questionnaire again in six months to a year and analyze the changes, if any, in the data. The sampling on a particular site should also occur over several days to capture the more transitory, and the potential more venerable, craft workers. Future research could also be undertaking to establish a more causal relationship between *safety culture* and accident rates on the job site. This is currently not well explored in the available literature.

Appendix A. Questionnaire in English

Demographics

1. Are you male or Female

Male

Female

2. What is your age?

18-20

21-29

30-39

40-49

50-59

60 or older

3. How long have you worked in the construction industry?

0-1 years

2-5 years

6-10 years

11 - 15 years

16 – 20 years

21 or more years

4. Do you work for the Prime Contractor or a Subcontractor?

Prime Contractor

Subcontractor

5. Are you a management/supervisor or are you a worker?

Management/Supervisor or Worker

Likert-type scale: (strongly disagree, disagree, neutral, agree, strongly agree)

Management

6. I feel that safety is as important as production to management.

7. Management listens to me when I raise safety concerns.

8. Safety hazards are quickly fixed by management.

9. Management only responds to safety hazards when there are accidents.

10. Employees that work safety are praised by management.

11. Safety lessons learned are shared with everyone on the site.

Safety Systems

12. The rules are there to keep me safe.

13. Safety rules are clearly explained.

14. Safety rules get in the way to doing the work.

15. The safety procedures are too complicated for me to follow.

16. Safety personnel support me working safety.

17. The housekeeping on the site is a priority.

18. I am provided the safety equipment I need for the hazards I face on the jobsite.

Risk

19. Safety equipment is only necessary for novices.

20. I work areas I know there are safety hazards.

21. I find PPE, such as hard hats, gloves, and fall protection, uncomfortable.

22. When my supervisor isn’t around I don’t follow the proper procedures.

23. I continue to use equipment that have broken or disabled safety features.

24. I don’t think that I will be involved in an accident this year.

Work Pressure

25. I work under a great deal of pressure to get the job done.

26. Safety can get in the way of production.

27. I take shortcuts in safety to meet production goals.

28. Coworkers take shortcuts in safety in order to meet production goals.

Competence

29. I receive the training I need to work safe.

30. I don’t know how to use the safety equipment I need to work safe.

31. I am able to identify safety hazards in my work area.

32. I actively look for safety hazards on the jobsite.

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Smart wearable technologies to promote safety in aging construction labor

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Abstract

Societies across the globe are facing aging populations that present significant challenges in the design and construction of high-rise buildings. In the wake of this demographic change particular attention must be paid to an aging workforce's safety on-site and the impact that smart technologies could have in the prevention of accidents from a worker's lack of functional capacity.

This study aims to develop a questionnaire survey to collect the required data on the monitored activities older construction workers perform, and the implementation of this monitoring for the prevention of accidents on-site. Initially, the smart technology that is crucial to the adoption of such an approach will be introduced. Next the history of wearable technologies, both successfully and unsuccessfully applied to elderly users, will be analyzed. Consequently, and drawing on the primary data gathered via the questionnaire, this study will present relevant information from 15 small and medium-sized construction firms. This study uses statistical methods to represent a basic approach towards identifying significant factors from the questionnaire results. Finally, it will be shown that this data will prove useful to researchers, contractors and construction companies within the scope of effectively integrating gerontechnology in the construction stage of projects.

Peer-review under responsibility of the scientific committee of the Creative Construction Conference 2019.

Keywords: construction safety, gerontechnology, wearable technology ;

1. Introduction

Technological development is rapidly increasing around the world, and smart technologies are an increasingly important field of research as changing demographics make an impact on the demand of new markets which could benefit older users. The construction industry is one of the most prolific industries in the Korean economy but, in the period from 2008 to 2017, the construction sector was second amongst all production sectors in terms of the frequency of injured workers and represented some 28% of the overall workplace mortality rate [10]. The construction industry has thus become one of the most dangerous sectors within which to work in Korea.

In the face of such statistics it is now widely agreed that wearable devices (WD) have the potential to transform safety in the construction industry. The research problem thus becomes how WD are perceived by construction companies and individual users, and how those perceptions influence WD adoption and applications in a working environment.

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2. Literature review

For the purpose of this research, the term “gerontechnology” refers to the use of technology concerned with aging; it can be defined as the development and adaptation of technology toward the goals and ambitions of aging and aged people [3]. Today much information about gerontechnology is being published while, at the same time and almost unceasingly, different policies, technologies, and innovations are reviewed by professionals concerned with age-associated changes [11]. Several studies [12], [13], [14], [15] have highlighted different methods for the implementation and adoption of technologies for improving daily activities and the quality of life of older people.

Technologies like smart wearable devices are defined as any technology that is worn by a user in the form of an accessory with integrated electronic and computing technologies, and that captures or reports some type of data. The wearable device can collect and store data from the user’s physical activity, movement, heat rate, and even audio data, any or all of which can later be analyzed. In Korea, one in every five people own a wearable device, with 13.3% using a smartwatch, and 1.2% using smart glasses [9]. Though the smartwatch segment continues to be the leader in wearable devices, Gartner predicts strong growth in the ear-worn segment [4]. In 2014, the global market for wearables was worth $9.2B [5], with a forecast to be more than $84 billion in 2022 [4]. This could mean easier access to participants as technology demands will increase and a major portion of the population will likely already be using a wearable device.

Changing technologies have shifted the application of digital technologies towards the well-being of aging adults by providing activity tracking, health coaching, health monitoring, and so forth. [3]. Acceptance of smart wearable devices is affected by a wide range of factors (social influence, perceived usefulness, and attitude towards use, among others) related to both the physical and cognitive changes accompanying the process of aging [6]. Research by MaRS Discovery District, a large-scale innovation center, suggests baby boomers will be the next group of primary adopters of smart wearable technology, denoting the importance of exploring factors surrounding their adoption by this aging segment of the population [5]. Hence, positive attitudes and the acceptance of these devices are vital to their successful incorporation into working environments such as construction sites.

REFLEX by Kinect is a smart wearable device that aims to capture the user's biomechanics to determine when they are moving with an incorrect posture. The novelty of REFLEX is the social encouragement it gives to users by setting personal goals and inspiring friendly competition in order to reduce unsafe postures and encourage better work habits. In addition, the collected data provides the user with real-time feedback to reduce the likelihood of injuries [6].

Myant SKIIN is a clothing-based wearable where sensors and actuators are directly knitted into the clothing making it feel like any other everyday undergarment. This technology is capable of capturing health data such as heart rate, temperature, activity, hydration and measuring body fat [7]. The data is then transmitted to the SKIIN Platform where the health information can be consulted and assessed, allowing older workers to remain independent without facing a plethora of repeat visits to the hospital or health clinic.

Both of the smart wearable devices above offers the benefits of being incorporated into daily activities without being disruptive to the working cycle of the older-individual. As previously stated, a key factor in incorporating this technology into the working environment is the positive attitude and acceptance by the user. Currently, there is not an explicit theory to explain and predict the adoption rate, acceptance, or the decision to use a WD, but the Unified Theory of Acceptance and Use of Technology (UTAUT) can provide insight as to some relevant factors [4]. The UTAUT has been used to study caregivers use of e-health interventions [3], adult use of virtual reality in a clinical setting [3], and occupational therapists intended use of virtual gaming with older adult clients [3].

Previous reports indicate that occupational accidents are detrimental to employee health on construction sites; this study analyses the use of wearable devices as an intervention method to monitor and generate improvements in older worker construction safety, as well as decreasing the risk of accidents. Technology product managers must identify opportunities to compete effectively for share and value in smartwatches, head-mounted displays for VR and AR, ear-worn devices, wristbands, and smart garments [4]. The existing literature does not yet address these factors with regards to WD adoption in the construction sector; this is the research gap this study aims to fill.

3. Theory

In order to address wearable technology solutions for an aging labor force in Korea, and recognizing the importance of this factor in this implementation, it was necessary to analyze the data stored in both the Korean Statistic Information Service and the Construction Safety Management Information System. Within these two governmental databases the records of the last ten years related to the status of accidents in the Korean construction site were explored in order to identify the main labor problems, specifically for the accident type, the accident cause, and any relation to the aging workforce. The importance of this data is in detecting the main problems that might have been prevented or even solved with a technological intervention.

3.1. Types of accidents at the construction site and causes

As shown in Fig. 1 [2], the highest risk of accident is related to a collapse of materials, accounting for 32% of all occurrences and representing 43% of overall fatalities and 42% of all injuries, between 2008 and 2018. Second behind collapse, falls also prove significantly dangerous for construction workers (16% of occurrences, 14% of fatalities, 12% of injuries). Combined, these two dangers represent 48% of occurrences and could point to the sorts of problems and hazards the construction industry and its aging labor force might address through the adoption of smart WDs.

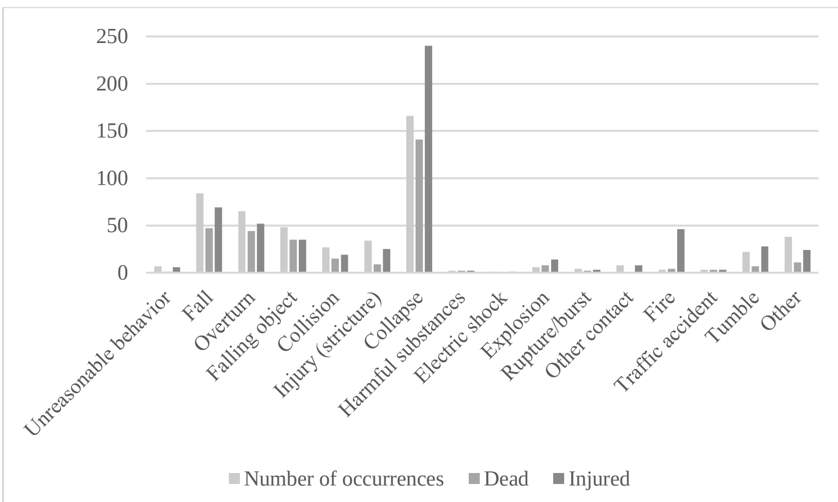

Fig. 1. Type of accidents at the construction site

The Korean Statistic Information Service registered a total of 518 accidents on construction sites of which the most common cause was improper construction operations. This cause was responsible for an overwhelming total of 118 deaths representing 36% of the workplace fatalities in the construction industry and 25% of all construction workers injured. Overall, with a total of 286 accidents we can confidently state that 55% of accidents are due to improper construction operations, operational error, and inappropriate worker behavior.

3.2. Aging society and the South Korean construction industry

The number of older adults (+60 years) in the Korean construction labor force has risen almost threefold between 2009 and 2017 (Fig. 2) from approximately 93,000 to 276,000, with the elderly share of the Korean population increasing from 5 percent to 14 percent during that same period. The increasing number of older adults we can expect in the future creates an impetus for making significant improvements to the risk of accidents, construction related injuries and deaths, and the overall older worker welfare in the Korean construction industry.

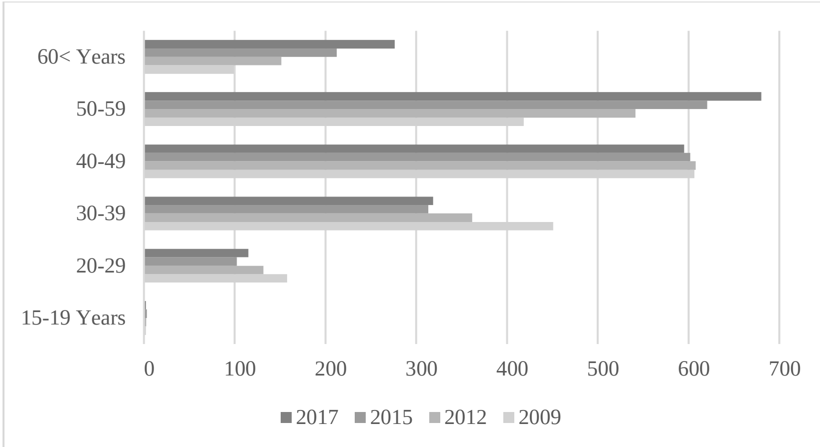

Fig 2. Employed persons by age group (in thousand persons) [1]

3.3. Device and equipment selection

A review of the different wearable devices was conducted to produce Table 1, and each device's unique features outlined. The selection criteria for the devices included functionalities and feature sets that may be useful for monitoring older adult health factors and exploring how suitable their advantages are to prevent construction accidents.

Table 1. Device and equipment fitting application

Device	Properties	Advantage to diminish types of accidents in elder workers	Limitations	Fitting application
Smartwatch	User-friendly interface with both touch and voice commands	Physiological wellness, navigation, fitness/activity tracking, heart rate monitoring	Battery limitations and outdoor/indoor inadequacy	x
Head-mounted display	Controlled by touching the screen, head movement, voice command, and hand movements.	Task coordination, visualization of scenery and information, AR/VR, easy communication	Motion sickness, battery life and price	Collapse and fall warnings
Smart clothing	No visual interaction with user via display or screen, data is obtained by body sensors and actuators	Heart rate, daily activities, temperature, and body position tracking	Ensuring the electronics still work after repeated washing	Alerting mechanism fit for fire alarm, fall and collapse alerts
Ear-worn	User-friendly interface with both touch and voice commands	Ambient noise reduction, hands-free calling, multi-device connections, and activity tracking	Battery life and power	Vital signs monitor fit for fall and collapse alerts
Wristband	User-friendly interface, accurate data is obtained through algorithms and sensors	Can detect oncoming dangers and immediately send this data to an outside manager or technical specialist for assistance.	Battery life and power	Fall and collapse alerts

4. Analysis of figures

We have analyzed a variety of wearable devices that are currently on the market for use by older people; identified a theoretical framework to support the acceptance and use of technology by older users; assessed labor challenges in the Korean construction industry; considered the steady increase of older labor in this industry, and; produced a comparison table to serve as a guide by which to incorporate selected wearable technologies according to the needs of the specific construction company.

Previously, a gap in the literature was identified and, hence, the assertion of 11 fundamental factors that influence older user adoption of technologies in the workplace served as the basis for the development of a questionnaire for 15 small and medium-sized construction firms. This research survey expands on findings from a prior study conducted by the researchers Debnath A., et. al. [8], wherein a survey was used to detect the dominant factors on the acceptability of wearable devices in Bangladesh.

The research emphasized in the study data and enumerated in the integration of wearable devices factors [6] suggests adopting safety technology can curb the increasing number of workplace injuries and fatalities in the construction industry. Thus, individuals were asked to rate the importance of these factors with a response range from 1-4, where 1 represented *no importance* at all, and 4 represented *most important*. According to the responses offered, the various factors were prioritized, and technological solutions recommended.

4.1. Survey

The qualitative survey research covers the perceptions of 15 professionals from within the industry and was composed of two sections: a background section and a main section. The background section was designed to discover more about the construction company participant's knowledge; hence, the participants were questioned with regards to: 1) the type of company they worked for, 2) their primary role within the company, 3) their years of experience, 4) their level of understanding of safety on a construction site, 5) their level of understanding of wearable devices as a means of deploying smart technology in the construction industry. The second and main section emphasizes the factors affecting the adoption of wearable devices in Korean construction companies [Fig. 3], so the participants answered, according to their professional perspective, as to which factors had a major impact in the implementation of wearable technology for their aging labor force activity monitoring as deployed in their own construction company.

4.2. Data analysis and results

The observed results [Fig. 3] indicate that the primary factor identified by participants impacting acceptance was *perceived risk*, followed by the *perceived cost*, *perceived trust*, and *lack of knowledge*. As shown in Table 2, the best means to target the perception of risk, cost, and trust in wearable devices is by endorsing assertive measures to enhance the acceptance and implementation of this technology. Specifically, this can be achieved by providing information about where the construction industry is heading and presenting the potential increase of profit the companies could expect by adopting such devices for their aging workforce. In contrast to existing research [8], quantitative analysis demonstrates that the *perceived ease of use* and *social influence* were not significantly associated with acceptance of smart wearable devices among the sample.

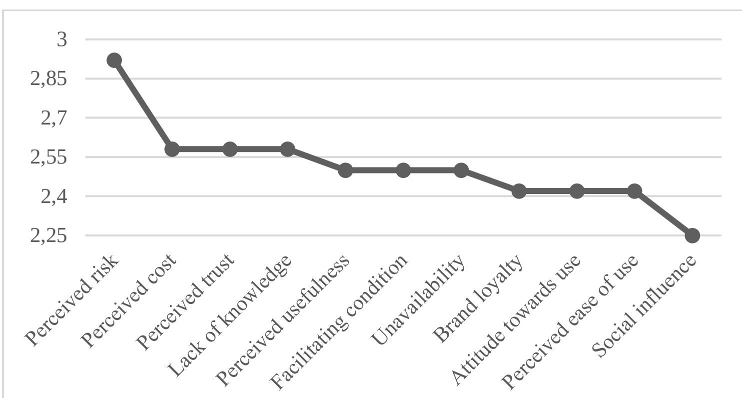

Fig. 3. Data analysis of acceptance factors

As a result, theoretical considerations of prioritized factors for the use of wearable technology must be taken into account when seeking their adoption by companies. This data will prove useful to construction companies by providing a scope of the ways by which to implement the technology and the solutions available for adoption in the construction sector.

Table 2. Data analysis and technology correlation

Factors	Factor solution
Perceived risk	Reducing complexity of usage, cost-effective acknowledgment
Perceived cost	Present the increase of profit in long term, technology education
Perceived trust	Achieved by eliminating consumers' perceptions of risk
Lack of knowledge	Assertive promotional measures
Perceived usefulness	Comparing effectiveness and profits with WD usage
Facilitating conditions	Provide a support system to facilitate the understanding of the devices

5. Conclusion

The present research serves as a platform on which to develop guidelines to properly integrate new wearable technologies into a construction environment where age-associated limitations will become more common as the demographic pyramid continues to invert. Of course, given the small sample, the use of a convenient sampling method, and the large number of dimensions being tested for association and correlation, the research has some limitations. However, this research generated several important elements of background information about the advantages of wearable devices adoption by the elderly in other sectors and provides key factors for this technology adoption in the South Korean construction industry.

Improper operations and improper behavior by workers are two of the main causes of safety issues in the construction industry and both frequently cause labor to experience injury and even death. In the face of this reality, the deployment of wearable devices in the work environment can help monitor work processes, create a healthier and safer workplace, and improve the prodictivity of personnel. With the continuous advancement and innovation in technology, it can be expected that construction safety issues will, in time, find a broader range of affordable smart wearable technologies available for adoption.

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Social identity, safety climate and safety behavior among mine construction workers

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Abstract

Creating a sound safety climate is accepted as an effective measure to curb unsafe behavior, which is the primary cause of construction accidents. However, the issue is open to debate as to which factors contribute to a sound safety climate. Using questionnaire responses from mine construction workers, this paper examines the impact of social identity on safety climate and hence safety behavior based on the structural equation modeling technique. Results show that workers who identify themselves primarily with their crews have stronger safety climate perceptions, while those workers who have stronger identification with the construction project have weaker safety climate perceptions. Surprisingly, group safety climate fail to mediate the relationship between workers' group identity and their safety behavior. The results highlight the role of crew leaders in creating a sound safety climate and curbing unsafe behavior.

Keywords: Mine construction workers; Safety behavior; Safety climate; Social identity; Structural equation modeling

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1. Introduction

The construction industry is notorious for the frequency of work-related accidents in China. According to the Ministry of Emergency Management, in the first half year of 2018 the construction industry has seen the largest number of work-related accidents, outnumbering the notorious mining industry for nine consecutive years[1]. Furthermore, the ministry found that failure to fulfil safety responsibility and prevalent safety violations are the primary causes. Enterprises fail to fulfil safety responsibility reflects that they don't attach importance to safety performance. In other words, they fail to prioritize safety over other competing operational objectives. Safety climate is defined as "shared perceptions with regard to safety policies, procedures, and practices[2]", and hence indicates the priority of safety. In a strong safety climate, management commits to safety and employees are involved in safety management. Failure to fulfil safety responsibility is indicative of a weak safety climate. Violations are behaviours [3], and safety violations are unsafe behaviours. Traditionally, regulatory bodies turn to enforcement-based systems in order to improve construction safety performance. Although the enforcement-based approach was effective in reducing accident and fatality rates, the rates are still at an unacceptably high level. Previous research[4][5][6][7] suggests that a strong safety climate is

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conducive to increasing safe behaviour. Therefore, measures which help the strong safety climate emerge are supposed to help cultivate safety behaviour. However, the literature is unclear about the antecedents of safety climate[7]. To fill in this gap, this research introduces social identity as an antecedent of safety climate.

The construct of social identity is relevant to construction practice and related to safety climate perceptions. At large construction sites, many different social subgroups (e.g., concrete work crews) exist along with their own peculiar values and goals. On a daily basis, construction workers interact with co-workers in their subgroups. Further, they are also supposed to follow instructions from the site management. Therefore, they identify themselves in terms of both their crew and the construction site, i.e., they have both group identity and project identity. Different subgroups have different interpretations of the project-wide safety policies and procedures espoused by the site management (i.e., project safety climate) and the safety practices enacted by crew leaders (i.e., group safety climate). Based on questionnaire responses from 478 construction workers at two large Danish public hospital construction sites, Andersen et al. [8] found that workers identify themselves predominantly with their work crew, and to a lesser extent with the construction site. Further, they found that social identity and safety climate are related both at the work crew and construction site levels, and the association between social identity and safety climate is stronger at the work crew level. Similarly, in this paper we hypothesize:

H1: Social identity is positively associated with safety climate at both the work crew level and project level.

H2: The association between social identity and safety climate is stronger at the work crew level than at the project level.

H3: The association between group safety climate and safety behaviour is stronger than that between project safety climate and safety behaviour.

The hypothesized structural model is shown in Figure 1.

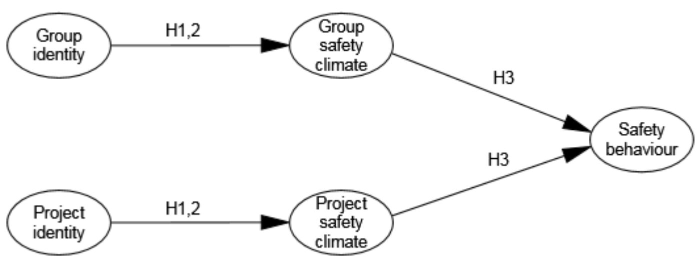

Fig. 1. Hypothesized structural model

2. Methods

2.1. Participants

After obtaining the clients' approval, an author visited two mines between February and March 2019, administering questionnaires in person. Respondents were assured that completion of the questionnaire was voluntary and responses were used only for research purposes. In total, 300 hard-copies were sent out and 212 valid responses secured, with a response rate of 70.7%. Table 1 shows the demographic characteristics of respondents.

Table 1. Demographic characteristics of respondents

Characteristics	Frequency	Percentage (%)
Gender		
Female	0	0.0%
Male	212	100.0%
Age (years)		

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<=20	1	0.5%
20—25	25	11.8%
26—30	63	29.7%
31—35	58	27.4%
36—40	41	19.3%
41—45	22	10.4%
46—50	2	0.9%
Education level		
Below primary	5	2.4%
Primary	36	17.0%
Junior high school	66	31.1%
Senior high school	75	35.4%
Technical secondary school	17	8.0%
Junior college/diploma	9	4.2%
College or higher	4	1.9%
Industrial experience (years)		
<=0.5	5	2.4%
0.5—1	27	12.7%
1—2	54	25.5%
2—5	53	25.0%
5—10	41	19.3%
10—15	21	9.9%
15—20	6	2.8%
>20	5	2.4%
Current job tenure (months)		
< 0.25	7	3.3%
0.25—3	17	8.0%
3—6	62	29.2%
> 6	126	59.4%

2.2. Data Analysis

Based on questionnaire responses, the authors tested the hypotheses with the structural equation modelling (SEM) technique. The reasons are twofold. First, it is difficult to measure the constructs involved in the hypotheses directly. In this case, SEM allows multiple measures instead of one single item representing a latent construct, and this provides more adequate representation than using only one single measure. Second, theoretical or abstract concept is unavoidably subject to measurement error which is basically due to inaccurate responses. SEM accounts for the amount of measurement error and present more accurate relationships between constructs.

In general, the SEM technique has two components, i.e., a measurement model assessment component and a structural model assessment component[9]. The measurement model represents how a set of indicators (or measures) come together to represent constructs, whereas the structural model shows how constructs are associated with each other. The measurement model assessment component is to measure the reliability and validity of an indicator or a set of indicators in representing the intended constructs. Reliability refers to the degree to which the indicator or the set of indicators is consistent in measuring the intended construct, and validity refers to the degree to which an indicator or the set of indicators is free from systematic errors in measuring the intended construct. After obtaining reliable and valid measures of the constructs, the structural model assessment component is to estimate the relationships between constructs. Hypotheses are supported when a) the structural model achieves acceptable goodness-of-fit and b) path estimates measuring the hypothesized relationships are statistically significant and in the hypothesized direction.

3. Measures

3.1. Group Identity and Project Identity

To measure group identity and project identity, three items were used from Choi et al. [10]. They were formulated towards both the work crew level and construction project level, e.g. "I am happy to be a member of my crew" (work crew level), and "I am happy to be a member of the project" (project level). A five-point Likert scale ranging from "Strongly disagree" to "Strongly agree" was used.

3.2. Group Safety Climate and Project Safety Climate

To measure group safety climate, three items were adopted from Zohar and Luria[11]. A sample item was "My direct supervisor refuses to ignore safety rules when work falls behind schedule." To measure project safety climate, three items were also adopted from Zohar and Luria[11]. A sample item was "Top management in this project invests a lot of time and money in safety training for workers." A five-point Likert scale ranging from "Strongly disagree" to "Strongly agree" was used.

3.3. Safety Behavior

To measure safety behavior, three items were adopted from Neal et al. [12]. A sample item was "I use the correct safety procedures for carrying out my job." A five-point Likert scale ranging from "Strongly disagree" to "Strongly agree" was used.

4. Results

4.1. Construct Reliability and Validity

In assessing the overall goodness-of-fit of an SEM model, Hair et al.[7] suggest four indices, one incremental index (e.g., comparative fit index, CFI), one absolute index (e.g., root mean square error of approximation, RMSEA), the chi-square (χ^2) value and its associated degrees of freedom (df). Many indicators are used to assess the reliability and validity of an indicator or a set of indicators in representing the intended constructs. A widely used reliability indicator is the Cronbach's alpha, with a threshold value of .70[7]. Two commonly reported types of validity are convergent and discriminant validity. Convergent validity is the "extent to which indicators of a specific construct converge or share a high proportion of variance in common[7]". Reliability is an indicator of convergent validity. Another indicator of convergent validity is the average variance extracted (AVE), which is calculated as the mean variance extracted for the indicators of the construct. As a rule of thumb, an AVE value of no less than .50 is indicative of adequate convergence. Discriminant validity is the "extent to which a construct is truly distinct from other constructs[7]". The discriminant validity of two constructs is secured if both of their AVE values are greater than the squared correlation estimate between them. Evidence of both convergent and discriminant validity is available after assessing the measurement model. After rounds of modification based on model diagnostics such as standardized residuals and modification indices, a final measurement model with acceptable goodness-of-fit is shown in Figure 2. Table 2 shows means, standard deviations, Cronbach's alpha, correlations, and AVEs of the latent constructs in the final measurement model.

Table 2. Means, standard deviations, Cronbach's alpha, AVEs, and correlation matrix

Constructs

Constructs	Cronbach's alpha	Mean	Standard deviation	GI	PI	GSC	PSC	SB
GI	.856	4.21	.623	.56	—	—	—	—
PI	.899	4.30	.687	.684*	.77	—	—	—
GSC	.875	4.31	.557	.653*	.513*	.71	—	—
PSC	.918	4.51	.639	.358*	.397*	.351*	.79	—
SB	.929	2.92	1.538	.005	.133	.132	.204*	.81

Note: 1) GI = Group identity; PI = Project identity; GSC = Group safety climate; PSC = Project safety climate; SB = Safety behavior. 2) Correlations between constructs are below the diagonal. AVEs are in italics on the diagonal. 3) * $p < .05$.

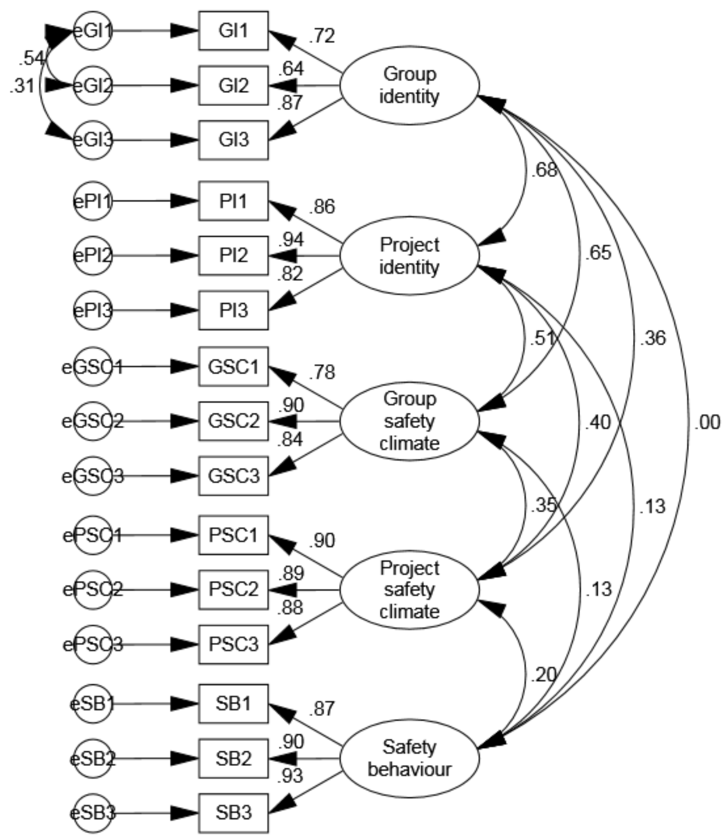

Fig. 2. Final measurement model (χ^2= 147.41; *df*= 78; CFI = .970; RMSEA = .065)

As shown in Table 2, the Cronbach's alphas were all greater than .70, suggesting construct reliability. All AVEs were no less than .50, suggesting convergent validity. The AVEs of any two constructs were greater than the squared correlations, suggesting discriminant validity. Furthermore, all the factor loadings were statistically significant at the .001 level (two-tailed), and also no less than the threshold value of .60.

4.2. Structural Model and Hypothesis Testing

Figure 3 shows a final structural model with acceptable goodness-of-fit. As shown in the figure, except the standardized path coefficient on the path in red (i.e., .06 on Group safety climate→Safety behavior), all other standardized path coefficients were significant.

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Hypothesis 1 states that social identity is positively associated with safety climate at both the work crew level and project level. As shown in Figure 3, the standardized path coefficient on the path of Group identity→Group safety climate was .68 ($p < .001$), and that of the path of Project identity→Project safety climate was .41 ($p < .001$). Hence, Hypothesis 1 was supported.

Hypothesis 2 states that the association between social identity and safety climate is stronger at the work crew level than at the project level. Since the standardized path coefficient regarding the former association (i.e., .68, $p < .001$) was greater than that of the latter association (i.e., .41, $p < .001$), Hypothesis 2 was supported.

Hypothesis 3 states that the association between group safety climate and safety behavior is stronger than that between project safety climate and safety behavior. Because the standardized path coefficient on the path of Group safety climate→Safety behavior was not significant, Hypothesis 3 wasn't supported.

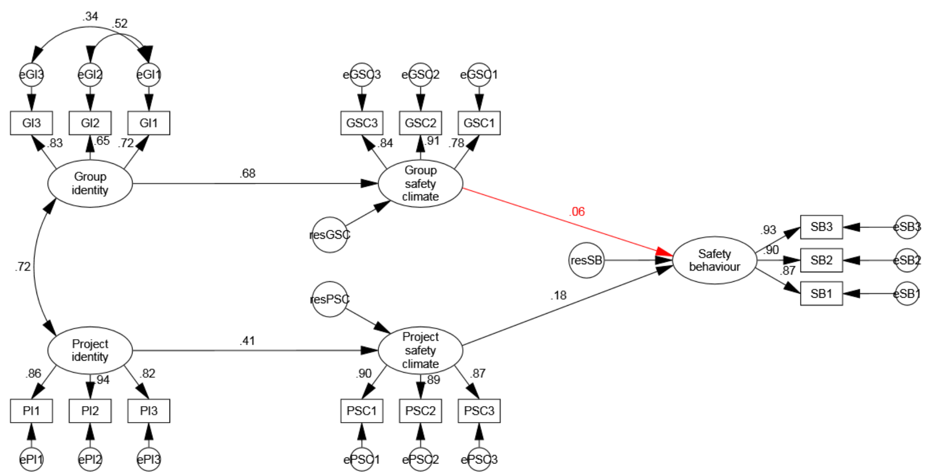

Fig. 3. Final structural model (χ^2= 157.91; *df* = 83; CFI = .968; RMSEA = .065)

5. Discussion and Conclusion

Social identity has implications for safety climate perceptions. At large construction sites many different social subgroups (e.g., concrete work crews) exist along with their peculiar values and goals, and different subgroups have different interpretations of safety rules, i.e., safety climate perceptions. This paper examines two types of social identity (i.e., group identity and project identity), and their associations with safety climate at two levels (i.e., work crew and project). Results show that group identity is positively associated with group safety climate while project identity is positively associated with project safety climate. Further, the association between social identity and safety climate is stronger at the work crew level than at the project level.

However, contrary to the hypothesis, group safety climate doesn't mediate the relationship between group identity and safety behavior. This indicates that crew leaders have not yet fulfilled their safety responsibility, and future interventions should make up for this deficiency.

The study is not without limitations. The biggest concern is the use of a cross-sectional design, which makes it difficult to draw causal inferences. Future research shall employ a longitudinal design to present a more comprehensive picture of the effects of social identity on safety behavior.

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Sustainable Construction Practices Challenges- A Stakeholders Perspective

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Abstract

Sustainable construction practices not only benefits government, environment and occupants but it secure the earth for future generations to come. Thus the paper discussing sustainable construction practices challenges in the construction industry of South Africa. Structured questionnaires were distributed to different construction companies and construction professionals. From the 75 questionnaires distributed, 60 were brought back and they were all valid and usable. Findings from the survey results obtained from the chosen respondents revealed that the is a lack of training in an organization regarding sustainable construction, lack of awareness of sustainable construction practices, lack of sustainable environmental materials, changes in material prices and escalations, lack of accessible guidance, lack of technical skills, resistance to change in adoption and material scarcity. The construction industry needs to promote and create more workshops on sustainable construction practices so that more stake holders would be aware of it benefits and incentives should be provided to organization that are implementing sustainable construction. Furthermore, the implementation of construction principles can be achieved successfully if all the construction stakeholders participates from design to completion of the project with the assistance of knowledgeable project manager on sustainable construction practices. The study will contribute to the body of knowledge by increasing more awareness of SC to professionals in order to be implemented.

Peer-review under responsibility of the scientific committee of the Creative Construction Conference 2019.

Keywords: Challenges; Construction industry; Sustainable construction; sustainable construction practices (SCPs); construction industry; South Africa.

1. Introduction

According to the Green Building Council of South Africa (GBCSA)[1], sustainable construction practices are good for the environment including the occupants of the building. The main goal of sustainable construction are driven by four factors namely minimizing the impacts of construction materials on the earth, minimizing the impacts during the period when the building is occupied and making sure that the occupants have a favorable living experience, minimizing the impact of the construction when the building is being demolished [2]. Sustainable construction practices does not benefits government, environment and occupants only but it secures earth for future generations to come [3].

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2. Construction Industry

The construction industry provides us with good infrastructure [4]. However, the construction industry has a negative impact on the environment which should be taken into consideration. [5] stated that construction has a detrimental effect on the environment. Research has shown that the environmental impacts of construction activities are grave and must be minimized [6]. Infrastructure and the construction industry contribute to 60% of raw materials extracted globally [7]. Construction plays a vital role in providing infrastructure for society while having negative impact on the environment and resulting to the depletion of resources [8]. The materials used during construction contribute greatly to depletion of natural resources [9]. The processing of material requires energy and could result in waste generation, materials that are sourced elsewhere require transportation and this leads to an increased energy consumption, in a long term this will have an impact on the environment [10]. These impacts occur from the onsite phase, to operational phase of the building until the demolition phase of the building, all these cycles of a building have an impact on the environment [11].

3. Sustainability

Sustainability refers to three aspects which are ecological, economic and social wellbeing [8], it also governs decisions concerning building materials. The aim of sustainability is to preserve raw materials, while promoting the effective use of energy and water, and the prevention of environmental degradation caused by the infrastructures that are being constructed [12].

4. Sustainable Construction (SC)

[12], describes the concept of sustainable construction as the present needs being met without limiting resources for future generations. SC is concerned with making eco-efficient and environmentally friendly buildings, this can start from the decision of which transport and materials must be used that will minimize the impact on the environment [10]. Hence, there must be policies put in place for material selection [13]. According to [14] companies can save money and benefit the environment significantly by sourcing the materials locally and making few trips from the supplier. Moreover, this process can help decrease the emissions, also reduce the carbon foot print by considering environmentally friendly alternatives for materials. The principles of SC must be applied in all the construction stages until demolition as well as the management of the resultant waste [11]. Stakeholders and the client must take responsibility of their role in mitigating the problem encountered with traditional buildings and adapt to the sustainable construction practices while maximizing the economic benefits [15].

SC practices have great benefits for the environment [16], therefore, the concepts and technologies that have a function to achieve sustainability as well as yield great satisfactory results during and after construction are: Lean construction; Building information modelling (BIM); Construction ecology; Biomimicry; Value management; Ecological economics; Life cycle costing; Life cycle assessment; Industrial building system (IBS); Nanotechnology; Ecological footprint; Design for the environment.

5. Sustainable Construction Practices Challenges

Different countries and industries are looking for ways to reduce climate change, pollution and their impact on the world's ecology [17]. The implementation of sustainable construction has been unsuccessful in many countries due to the challenges that limit the successful implementation of SC. According to [16], the sustainable construction technologies are very expensive and costly due to the limitation of the components not being sold locally. The adoption of sustainable construction practices is client driven [18], a client with good knowledge of the benefits will encourage the use of the practices but due to lack of awareness clients do not have knowledge on some practices and decided to continue with traditional buildings.

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The challenges that limit the implementation of sustainable construction practices are: The lack of training among construction stakeholders with regards to sustainable construction; The lack of participation from the government; The lack of knowledge regarding the legal aspects and regulations; The lack of understanding of sustainable practices by the client; The lack of financial and economic risks assessments in client organization; Lack of financial incentives; Resistant to change ;Misconceptions about sustainable construction practices; Lack of sustainable materials; Lack of public awareness. According to [11], the challenges of implementing some of the SC practices such as lean construction were: administrative view point, lack of legislation, lack of specialised angle and attitudinal perspective. Lack of knowledge on sustainable practices [16]. [19] observed negative perception as a challenge, therefore, better client perception will result in better understanding and demand of sustainable construction practices. SC can be introduced during the planning and design stage, engineers must have knowledge of SC as to minimize the environmental impact and incorporate sustainable construction [18]. Technologies like BIM are being used for planning and quality assurance procedures using software but barriers limiting the implementation are poor management and communication, the lack of availability of software, the lack of calibration and uniform procedures and the cost to implement such technologies [20; 17]

6. Research Methodology

6.1. Research area- Mpumalanga Province

Mpumalanga means the place of the rising sun and people are drawn to the province by its magnificent scenery, fauna and flora. The province is the second smallest province in South Africa yet it has fourth –largest economy. It’s situated mainly on the high plateu grasslands of the middleveld. Mpumalanga has network of excellent roads and railway connections thus making it highly accessible [21]. The province is a tourism destination and it’s a home, of over 4 million people, the principal languages are siSwati and isiZulu. The province is a summer-rainfall area divided by the escarpment into the Highveld region with cold frosty winter and lowveld region with mild winters and subtropical climate. Mpumalanga is the second largest citrus producing area in South Africa and is responsible for one third of the country’s export in oranges. Mpumalanga is very rich in coal reserves. The province house the country three major power stations, of which are the largest in the southern hemisphere [21].

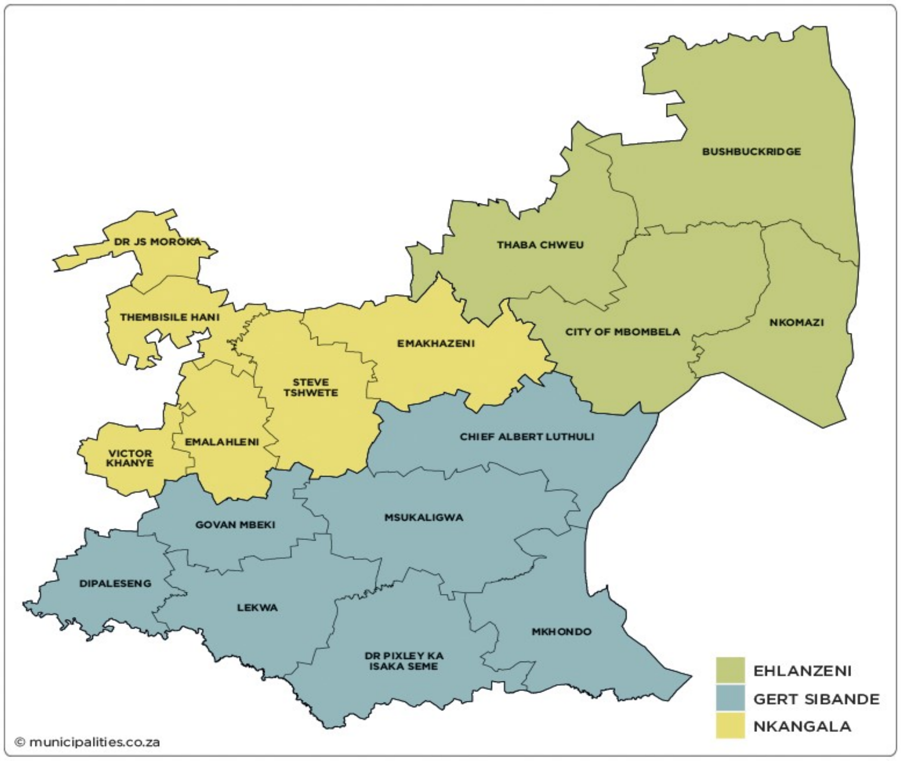

Figure 1: Mpumalanga map

6.2. Research area- Mpumalanga Province

Quantitative approach method was adopted to investigate a stakeholder's perspective on the challenges of implementing sustainable construction practices. The study was carried out in Mpumalanga Province of the Republic of South Africa. 75 Questionnaires were distributed and 60 were brought back which were all valid and usable. A well-structured questionnaire was distributed to different construction companies in the Mpumalanga Province, amongst construction professionals such as civil engineers, project managers, directors, quantity surveyors, construction managers and contractors who are register on the CIDB data base. The questionnaires were sent via e-mails, some were delivered to the known construction companies by the researcher and some were distributed during site clarification meetings of contractors and consultants bidders in Mpumalanga Province. The study was conducted from reliable scholarly sources such as articles, journals, books, publications, websites and site experience on the field.

6.3. Research area- Mpumalanga Province

5- point linkert scale was adopted for the study which gave a wider range of possible scores and increase statistical analyses that are available to the researcher. The first linkert scale read is on agreement form as follows:

1- Strongly Disagree (SD)
2- Disagree (D)
3- Neutral (N)
4- Agree (A)
5- Strongly Agree (SA)

The 5 point scales were transformed to mean item score abbreviated as (MIS).

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6.4. Computation of the mean item score (mis)

The computation of the mean item score (MIS) was calculated from the total of all weighted responses and then relating it to the total responses on a particular aspect. The mean item score was adopted to rank the factors from highest to lowest. The Mean Item Score (MIS) is expressed and calculated for each item as follows:

$$\textbf{MIS} = \frac{1n1 + 2n2 + 3n3 + 4n4 + 5n5}{\sum N}$$

Where;
n1 = number of respondents for strongly disagree
n2 = number of respondents for disagree
n3 = number of respondents for neutral
n4 = number of respondents for agree
n5 = number of respondents for strongly agree
N = Total number of respondents

7. Findings

7.1. Challenges of sustainable construction practices

The challenges of implementing sustainable construction practices in the Mpumalanga province construction projects were identified as the lack of training in the organization which was ranked number one with (MIS=4.30 &STD=0.941); lack of awareness of sustainable construction practices was ranked second with (MIS=4.24 & STD=0.949); lack of environmentally sustainable materials and change in material prices and escalation were ranked third with (MIS=4.19& STD=0.989 and 0.993 respectively); lack of accessible guidance was ranked fourth with (MIS=3.97 & STD=0.810); lack of technical skills was ranked fifth with (MIS=3.85 & STD= 0.998); resistance to change in adopting new practices was ranked sixth with (MIS=3.81 & STD=0.761); material scarcity and delay in decision making were ranked seventh with (MIS= 3.72 & STD=0.968 and 0.784 respectively); the price of implementing the practices and client worries profitability were ranked eight with (MIS=3.70 & STD=0.808 and 0.946 respectively); lack of incentives from the government was ranked nineth with (MIS= 3.69 & STD=0.838); lack of client demand was ranked tenth with (MIS=3.66 & STD=0.893); the fragmented nature of the industry was ranked eleventh with (MIS=3.56 & STD=0.981); lack of awareness of the benefits was ranked twelve with (MIS=3.54 & STD=0.815); potential time factor involved in implementation of new practices and lack of government support was ranked thirteen with (MIS=3.51 & STD=0.942 and 0.927 respectively); poor management and communication was ranked fourteen with (MIS=3.44 & STD=0.922); lack of awareness among professionals and human attitudes towards change was ranked fifteen with (MIS=3.41 & STD=0.818 & 0.922 respectively).

Table 1: Sustainable Construction Practices Challenges

Barriers	**Mean**	**Standard deviation**	**Rank**
Lack of training in the organization	4.30	0.941	1
Lack of awareness of sustainable construction practices	4.24	0.949	2
Lack of environmentally sustainable materials	4.19	0.989	3
Change in material prices and escalations	4.19	0.993	3
Lack of accessible guidance	3.97	0.810	4
Lack of technical skills	3.85	0.998	5
Resistance to change in adopting new practices	3.81	0.761	6
Material scarcity	3.72	0.968	7

Delay in decision making	3.72	0.784	7
The price of implementing the practices	3.70	0.808	8
Client worries profitability	3.70	0.946	8
Lack of incentives from the government	3.69	0.838	9
Lack of client demand	3.66	0.893	10
The fragmented nature of the industry	3.56	0.981	11
Lack of awareness of the benefits	3.54	0.815	12
Potential time factor involved in implementation of new practices	3.51	0.942	13
Lack of government support	3.51	0.927	13
Poor management and communication	3.44	0.922	14
Lack of awareness among professionals	3.41	0.818	15
Human attitudes towards change	3.41	0.922	15

8. Conclusion

Lack of training in an organisation, lack of awareness of sustainable construction practices, lack of environmental sustainable material, change in material prices and escalation, lack of accessible guidance were the top challenges of sustainable construction. Therefore, the government of South Africa is expected to conduct more workshops and training regarding SC to create more awareness among stakeholders. Since , in South Africa the adoption of sustainable construction practices is client driven its not a government mandate or a policy as yet, hence, the client must also attend such awareness training . Once the client has good knowledge of the benefits will encourage the use of the practices in their projects. Therefore, lack of awareness clients do not have knowledge on some practices and decided to continue with traditional buildings. It is recommended that contractors or companies who are already implementing the practices be encouraged through incentives or those construction material that promote sustainable construction be tax free and they must be readily available for the public to use.

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3D Printing Applications in Construction from The Past and into The Future

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Abstract

The advent of 3D printing technology may very well be remembered as one of the most important technological advances of the early twenty-first century. This technology is transforming the dynamics of the manufacturing world in ways that may have not been thought possible a couple of decades ago. 3D printing is now being used in medicine and dentistry to make prosthetic parts, sensors, and medical models among a number of other applications. The versatility of the types of materials that can be 3D printed makes the process extremely useful. The technology is being used in different industries to produce various parts and components for generally lower costs while achieving a better quality. This is either achieved by 3D printing the parts themselves or the molds that would eventually be used to make the parts. However, the construction industry has been slow in adopting this technology for many reasons, many of which still need to be investigated so a way can be found around them. In this paper the authors first examine the history of 3D printing applications in the construction industry. They then provide an overview of recent attempts at applying the technology while discussing the successes and challenges encountered. They finally propose solutions for resolving some of the identified challenges to help the industry move forward in taking advantage of this emerging and potentially beneficial technology.

Keywords: 3D printing, construction automation, construction technology.;

1. Introduction

Dictionary.com defines 3D printing as “a printing process that involves making three-dimensional objects from digital models by applying many thin layers of a quick-drying material on top of each other” [1]. The technology became possible because of significant advances in both computer and materials technologies that have been taking place in recent decades. 3D printing has gained substantial attention in all the manufacturing industries in the past few years. Considering the adoption of new technology, it is well established that the construction industry is generally lagging in this area. Many new experiments have been conducted in the construction industry to explore the full potential that 3D printing can bring. However, these experiments are very fragmented [2]. A critical review of the history and current development of 3D printing in the construction industry is therefore needed. This paper, aims to: (1) examine the history of 3D printing applications in the construction industry; (2) provide an overview of recent attempts at applying the technology while discussing the successes and challenges encountered; (3) propose solutions for resolving some

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of the identified challenges to help the industry move forward in taking advantage of this emerging and potentially beneficial technology.

2. A Historic Overview of 3D-Printing

The first 3D printing efforts are granted to Dr. Hideo Kadoma for his development of a rapid prototyping technique in 1981. Dr. Kadoma developed a system of printing solid layers of fast drying photopolymers that resembled a cross-sectional slice of a CAD model, and he called it Rapid Prototyping (RP) [3].

Three years later, Charles Hull patented Stereolithography which is a technique that utilizes the reaction between a liquid photopolymer and an Ultraviolet (UV) laser beam. When exposed to the UV light, the liquid photopolymer will instantly turn each layer into a solid plastic shape that is consistent with the 3D CAD model. Stereolitography was the first technology of rapid prototyping which means fast, precise and repeatable production of items usually with computer support. In 1992, Hull's company, 3D Systems, produced the SLA-1 which was the worlds' first commercial Sereolithography Apparatus (SLA) [4].

In 1987, Larry Hornbeck of Texas Instruments created Digital Light Processing (DLP) technique. This technique has many applications in the production of projectors and 3D printing. DLP technology uses digital micromirrors laid out on a semiconductor chip. Both DLP and SLA work with photopolymers, but they use different light source. DLP uses more traditional sources like arc lamps. Also, DLP uses a liquid crystal display panel that is being applied to the entire surface of the building material. DLP also uses a liquid plastic resin as a printing material. The resin quickly toughens when exposed to a large amount of light. DLP printing speed is fast compared to SLA. DLP creates more robust 3D objects with excellent resolution. It also uses less material which reduces cost and material waste. That same year, Carl Deckard introduced the Selective Laser Sintering machine (SLS) which is a similar technology that utilizes a powder photopolymer reaction rather than liquid [5].

In 1989, Scott Crump a co-founder of Stratasys Inc. filed a patent for Fused Deposition Modelling (FDM). FDM is a proprietary technology that is still held by the Stratasys Inc company today, and it is also the process used by many of the entry-level 3D printing machines [5].

Other 3D printing technologies and methods were also emerging during these years, namely Ballistic Particle Manufacturing (BPM) originally developed by William Masters, Laminated Object Manufacturing (LOM) originally developed by Michael Feygin, Solid Ground Curing (SGC) originally presented by Itzchak Pomerantz et al and 'three dimensional printing' (3DP) originally developed by Emanuel Sachs [5].

Throughout the 1990's and early 2000's many innovative technologies continued to be introduced, still focused mainly on industrial applications, and they were still mostly processes for prototyping applications. Research and Development were also being led by advanced technology providers for customized tooling, casting, and direct manufacturing applications. This saw the rise of new terminology, namely Rapid Tooling (RT), Rapid Casting and Rapid Manufacturing (RM). In 2005, the American Society for Testing and Materials (ASTM) recognized Additive Manufacturing (AM) as the standard term for all of these processes. ASTM defines additive manufacturing as "a process of joining materials to make objects from 3D model data, usually layer upon layer" [6].

The construction industry is well-matched to 3D printing because the information needed to create a 3D item exists as a result of the design process, and the industry is already experienced in computer-aided manufacturing. 3D printing provides the ability to use different materials, freedom of design, and the ability to fabricate complex shapes onsite or offsite. Add to those characteristics the power of automated and autonomous production, and you have a near-perfect match for the construction industry needs [7]. However, it should be noted that the application of 3D printing in the construction industry is still in its early stages.

3. 3D-Printing Applications in Construction

Construction 3D printing allows faster and more accurate construction of complex items as well as reducing labor costs and material waste. It might also enable construction to be undertaken in tough or dangerous environments not suitable for a human workforce such as in remote areas on earth and in space [8].

The first 3D printing attempt in the construction industry was in 1995, by Dr. Behrokh Khoshnevis. Dr. Khoshnevis used stereolithography technology to produce three-dimensional ceramic parts. A complicated ceramic part was produced although the mechanical properties of the part were not optimized [9]. In 1996, Dr. Behrokh Khoshnevis registered a patent entitled "Additive Fabrication Apparatus and Method". This patent reveals a device for producing 3D objects using additive fabrication methods. The device includes two nozzles for delivering fluid materials, two supply means for carrying the fluid materials to the nozzles, and two control means for moving and positioning the nozzles. An additional feature of the device is the use of trowels, which allow fast creation of smooth surfaces with high precision. The trowels permit formation of different shapes using only the two trowels, instead of using a variety of tools needed in traditional plastering [9]. Fig. 1. Shows Dr. Khoshnevis new device.

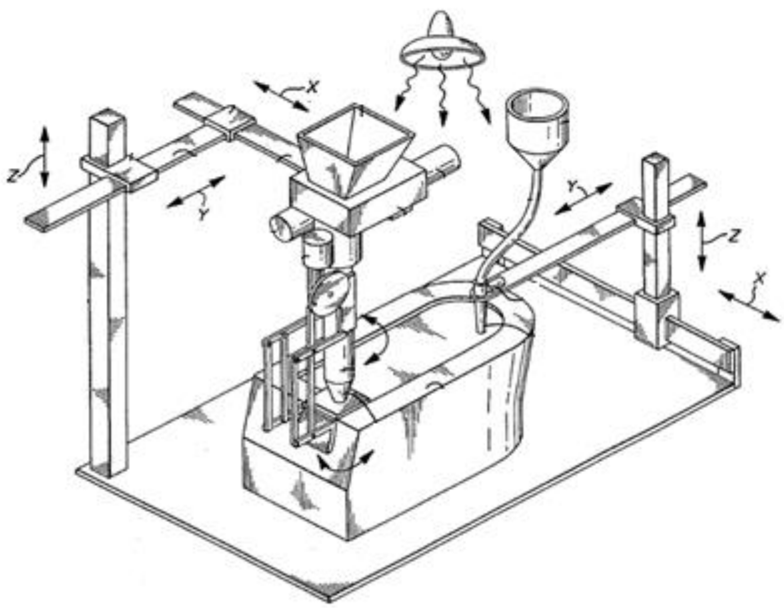

Fig. 1. Dr. Khoshnevis 3D printing device (adapted from Hinczewski,1998 [9]).

In 2001, Dr. Khoshnevis printed a wall using an FDM 3D printer that is mounted on a robotic arm to extrude concrete layers. Dr. Khoshnevis called this new technology Contour Crafting (CC). Contour Crafting can be defined as "an additive fabrication technology that uses computer control to exploit the superior surface-forming capability of troweling to create smooth and accurate planar and free form surfaces out of extruded materials" [10]. The Contour Crafting (CC) technology demonstrated all the qualities needed to use additive manufacturing on construction sites: reduction in costs, materials waste and accidents, faster construction speed, complex architectural shapes, and more. Contour Crafting also provides flexibility in building concrete shapes that were very hard to achieve in the traditional pouring methods; with that, houses can be built efficiently and environmentally friendlier [11].

In recent years and as technology improved, the use of 3D printing has been expanded to construction products other than ceramic. For example, 3D printers can now print plastic and nylon products which are commonly used as plug fixtures, window frame fixtures and plumbing fittings in building projects. More importantly, concrete printing has been proven to be feasible in printing geometrically complicated concrete products [12]. The size of the concrete products was limited using 3D printing. For example, the 3D printer in Lim et al. (2012) could only handle a print dimension up to 5.4m (L) x 4.4m (W) and 5.4m (H). However, such size would produce enough capacity to print basic precast concrete components. As such, the main issue of the use of 3D printers to produce construction parts is not related to the size, but rather whether there are enough flexibility and customization demands that can support the use of such technology to achieve economies of scale [13].

The popularity of the 3D printing technology has seen recently a significant increase with many new companies, including some backed up by prominent names from the construction industry and academia. This led to several important milestones, such as the first 3D printed building and the first 3D printed bridge [14]. However, the application of 3D printing in construction is still in its infancy and is bound by many limitations. 3D printing is not an isolated solution that can solve all the problems in the construction industry. There are several requirements, such as the scale of the project and printing materials, which should be fulfilled in order for the printing technology to perform at its maximum potential. Some of the challenges to 3D printing in construction are dealing with various trades that required the use of different materials and construction methods. Further, using completely automated 3D printing techniques to create a full house is still a challenge [14].

4. Challenges of 3D printing in construction

Many researchers argued that large scale buildings might not be printed using 3D printing technologies because of the size of 3D printers [15]. Gibson et al. (2002) said that most 3D machines had a relatively small build envelope. As such, the size of the printed model would be limited. Berman (2012) also argued that 3D printing technology was commonly useful to create small part sizes [15]. Many other scholars have also stated that the main limitation of 3D printing technology was the size of the printer needed to print the item [16].

Most 3D printers were small when the technology trend started. It remained unclear whether the technology could be used to print large-scale models or buildings as the size of 3D printers was directly related to the models or buildings it could print. However, in recent years, with the new development of 3D printers, there have been a lot of large-scale models or buildings that were printed using large-scale 3D printers [17].

In addition to the size of the printer, materials played a significant role in 3D printing. The printing materials should have some basic features such as quick hardening in order to be used in 3D printing [18]. There were many studies which found that the strength and stability of the printed products using current printing materials (such as plaster) might prevent the technology from being used in large-scale models or buildings. For example, Khoshnevis et al. (2001) found that although plaster has been frequently used as a printing material because it was commercially available, cheap, light in weight and quick hardening, the material demonstrated low wet-strength and a larger than 3% shrinkage [18]. Similarly, although clay demonstrated a better wet-strength compared with plaster, the stability of the printed products has only been tested in small object sizes [18]. The low availability of high-strength printing materials also led to the speculation that 3D printing might not be useful to create large-scale models or buildings.

However, recently, various materials have been modified and proved to be effective as high-strength printing materials. In order to be used as a printing material, concrete needed to have an acceptable degree of extrudability so that it can be extruded from the nozzle of the printer [19]. In addition, the concrete should bond together to form each layer and have adequate buildability characteristics to enable it to lay down correctly, stay in position and be stiff enough to support further layers without collapsing [19]. By changing the sand/binder proportions and the dosages of other admixtures in the mix design, a variety of compressive strength have been achieved, with the highest up to 107MPa (at 28 days). As such, it is realistic to assume that the strength of the printed concrete is high enough to be used in large-scale building projects as concrete of 60-100MPa is usually used in these projects [19].

All in all, 3D printing can be used to print large-scale buildings. However, there is low demand for small sizes and customized products in the construction industry when compared with other industries [20]. In addition, the materials (i.e. clay and concrete) need to be improved in terms of brittleness so they can be used to print large-scale buildings.

3D printing may also be more expensive than conventional construction due to the high cost of 3D printers and the fact that most people in the industry are unfamiliar with 3D printing technologies and applications. Although 3D printing will minimize the material waste, it incurs high up-front costs to create the digital model [21].

5. Current Trends in 3D-Printing

The initial point for any 3D printing method is the creation of a 3D digital model, which can be developed using a variety of 3D software programs. Then it is exported to a file in a common 3D data exchange format. For the 3D printing industry, the most popular format is STL (Standard Tessellation Language format). Next, for the majority of 3D printing technologies, the saved data is processed to decompose the model into slices. This results in a set of 2D

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contour lines that are further processed to generate control commands to position the printing head or laser beams [21]. As suggested by Canessa et al. (2013). Fig. 2 shows the typical 3D printing work-flow.

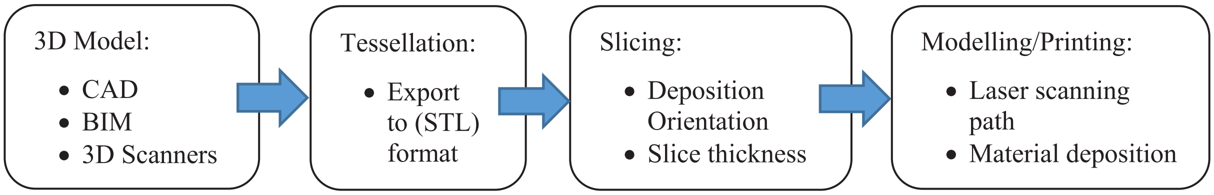
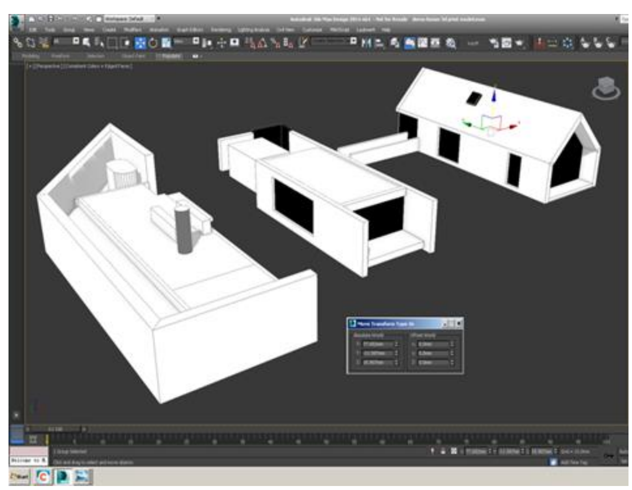


Fig. 2. 3D printing work-flow

While 2-D representations remain as the baseline method for project delivery in the construction industry, substantial time is needed to create digital models for 3D printing [21]. Traditional approaches of converting 2-D drawings to 3D models have many problems including low quality and inefficiency [22]. Building Information Modelling (BIM) is an emerging method for digital representation of physical and functional characteristics of a facility [23]. When compared with conventional 3D modeling tools, BIM covers not only geometry information but material performance (i.e., yield strength, tensile strength, shear modulus, thermal conductivity, etc.), spatial relationships and manufacture information [25]. Furthermore, objects in BIM are defined as parameters and relations to other objects. As such, one object change will trigger related objects to be changed automatically [24]. In the last few years, BIM has been proved as an effective method to facilitate 3D printing implementation in the construction industry [24]. BIM can be used in the 3D printing of small and large scale models and buildings.

BIM is more powerful than traditional tools in complex building design [25]. The interaction between 3D printing and BIM enhances the ability to produce 3D items rapidly from a BIM design without specialized or costly manufacturing equipment [25]. Most of BIM tools support the exporting process of generating a file in a proper format (i.e. STL) that can be directly converted into a set of instructions for the print [26]. Furthermore, BIM vendors such as Autodesk have collaborated with 3D printing providers to further simplify the process of 3D printing from BIM models. Further, 3D printing-integrated BIM supports the creative process of designers to produce variations of a single artifact or diverse artifacts at various stages of design [26]. Fig. 3 shows a 3D model that has been designed using BIM and printed using a 3D printer.

(a) 3D printed model



(b) 3D digital BIM model

Figure 3: BIM digital model and the 3D printed model [26]

Although the use of BIM can help examine the printed projects at performance and assembly levels, the life cycle assessment of the printed projects is still vague. In addition, the degree of customization of the printed items has not yet been empirically examined in the construction industry. It is expected that by addressing these challenges, the construction industry could maximize the advantages of the 3D printing applications [26].

5. Futuristic Perspective of 3D-Printing in Construction

There are different views about where the 3D printing technology could be headed. Although 3D printing is still in its early days in the construction industry, the potential benefits seem to be driving the technology forward. Till today, there is no building that is fully printed [26], 3D printing could use the advancement of automation and robotics to automatically print a full large-model. Tomorrow's construction engineers and managers need to master the software skills on which 3D printing rests. Learning to co-work with automated and 3D printing technology will be more and more a very important requirement for the workers in the construction industry.

3D printing could also be a way to explore space. Applications of 3D printing to build in space are unlimited. 3D printing reduces time, cost, and health, and safety risks if used in space. As a result, NASA has launched the "3D Printed Habitat Challenge" to develop innovative 3D printing capabilities to build homes in space.

3D printing technology could be used to increase sustainability. Houses can be built based on the material life cycle, that can be used in evaluating the environmental sustainability of building materials. Creating sustainable buildings with complicated shapes and that are adapted to their surroundings may become one of the biggest advantages for 3D printing.

6. Conclusion

The presented research gives a brief overview of 3D printing in construction. Regardless of the future of 3D printing in construction, it is clear that it will change the construction industry forever. Whether this is in creating new shaped structures or providing cheap housing, the buildings of the future will most likely look much different than those of today. However, the use of 3D printing is also subject to a few prerequisite requirements, mainly on applicability in large-scale building projects, the development of BIM, the degree of requirements on customization, and the life cycle cost of 3D printed construction products.

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A Study on a Conceptual Data Model for Developing a Building Fire Information Management System

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Abstract

Recently, as large-scale indoor fires have increased, fire-response systems that enable systematic and effective responses have become more important. Despite the need for the quick and intuitive gathering of relevant information for effective fire response, current information transmission systems are based on paper documents and the opinions of the people nearby. These actions can delay the response time and often cause inappropriate judgments. For an effective fire response in a building, it is important to quickly and intuitively collect and provide relevant information such as location data, available fire equipment, and risk factors in the event of a fire. Building Information Modeling (BIM) can be used in various ways from 3D visualization to spatial data management. Despite these advantages, utilizing data stored in BIM remains a challenge for emergency responders who respond directly at fire sites. This study aims to propose information requirements and conceptual data structure for the development of BIM based building fire information management system for fire response. This can store management history data and build a database so that the required information can be delivered quickly in case of a fire. Based on this paper, the proposed building data structure is expected to design a data model for the construction of the fire related information system database in the field of building disaster management. In future research, a system prototype will be developed with this conceptual model and its effectiveness will be verified by applying it in actual practice.

Keywords: Fire responase; Data model; Data management; Building Infomration Modeling (BIM)

1. Introduction

Building fires are difficult to predict and thus suggest the importance of managing and inspecting relevant information about facilities in buildings. Serious damage in building fires are caused by insufficient safety management and inspection systems, inoperative fire facilities in a building, or insufficient fire response manuals and behavior [1]. The issue of how to support and cope with a fire site quickly and accurately plays an important role in the early fire response. Therefore, emergency responders such as facility managers and rescue teams should be aware of the correct situation to make optimal decisions and should be able to analyze fire situations using all the information generated at

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the fire site [2]. Although they need to quickly and intuitively collect relevant information from the fire site, the current information system is based on paper documents and listening to the opinions of nearby people. These actions can delay the response time and often cause inappropriate judgment [3]. When a fire deteriorates, it is also important for the rescue team to utilize the fire facilities installed in the building, but such information is often unavailable and the utilization rate is poor [4]. Briefly, indoor spatial information including available fire facilities should be provided to rescue teams for effective building fire response [5]. Consequently, facility managers should store and manage such information in advance and transmit it immediately to the rescue team in a fire response.

Building disaster management, particularly for fires, must be managed through a consistent and systematic management system that goes beyond meeting the minimum safety requirements under existing law so that the latest building information can be provided to users immediately in a fire response. Building and indoor facilities information visualized in 3D can be intuitively understood in emergency situations [6]. Systematic information management can also improve the reliability of information. Building Information Modeling (BIM) is of increasing interest in consistent information management applications as "an approach to the digital representation of design, construction and facility management processes to facilitate data exchange and interoperability [7]" in the architecture, engineering, and construction industries. As the advantages of BIM application have been proved in each field of the AEC industry, the potential benefits of BIM are being discussed in fire safety and disaster management as it allows emergency responders to share location data and key information of critical elements in fire response in connection with information generated during the building operation and maintenance phase [6, 7]. Despite these advantages, BIM in the field of building fire safety and response remains poorly utilized as an information management tool, which means that object and attribute data goes under-utilized, which is the biggest advantage of BIM.

This study's main purpose is to confirm the information requirements of building fire response before constructing the database for the development of a Building Fire Information Management System (BFIMS). This paper constructs the data structure of information required for emergency responders in building fires to use 3D BIM technology, which can store object and attributes data as building elements. A system framework and development direction is proposed that can apply to the data model presented in this paper. The proposed data structure is derived from several previous published studies and practical data on the basis of building fire management. In addition, the current building fire response method was investigated and its limitations are identified. The information requirements for emergency responders were derived from expert interviews to design a data structure that reflected the information requirements. This was intended to improve the usability of reliable location data and key information of building elements and fire facilities for emergency responders. Consequently, it will likely improve the fire responsiveness of emergency responders in building fires.

2. Current Building fire response method and limitations

Disaster management refers to all activities involved in the prevention, preparation, response to, and recovery from disasters in accordance with the sequence of time activities. The response phase is all types of activities that minimize the loss of life and property by prompt action in the event of a disaster. In the building fire response, facility managers and rescue teams play an important role as the main body of action capable of a direct response in the early stages of fire occurrence.

Occupants who are unfamiliar with the building tend to choose routes that are relatively inadequate because they do not recognize evacuation facility information such as emergency exits and emergency stairs [8]. As the building's size increases, it becomes more difficult for them to recognize escape routes easily because the general route and evacuation route are separate. In this situation, the facility manager has a significant impact on occupants' behavior [9]. Facility managers conduct disaster prevention and preparation such as building safety checks, emergency drills, real-time monitoring, and announcement inspections. For example, the facility manager should inspect and record the operation and function of fire-safety related facilities at least once a year depending on the building's size. However, these records typically only document the results of actions against malfunctions, so most of the data is temporary. Therefore, systematic data management is insufficient and it is almost impossible to use related information in a fire response.

The rescue team arrives at the fire site within 5–10 minutes after the fire notification and receipt. During the short dispatch process, they receive the schematic drawings to their mobile devices such as the site commander's desktop PC and grasp the building's approximate size and shape. However, the rescue teams can only receive information on specific buildings as specified by law and most relevant information is collected by the rescue teams about the surrounding data sources (nearby residents, victims, building-related people, fire activity information card, etc.) after arrival at the fire site. Even if they have drawings in advance, changes are not reflected during use, so there may be no link between the actual building and the drawing. In addition, two-dimensional drawings have limited capability to express complex spatial relationships in large-scale buildings [10]. These practices will likely collect inaccurate information at confusing fire sites and making optimal decisions takes too much time [11].

When the rescue team extinguishes the fire inside a building, they have difficulty identifying the internal situation due to flames and smoke and difficulty judging the method of suppression due to their lack of knowledge about the building. In particular, if a fire continues, they have to utilize firefighting facilities installed in the building besides the prepared equipment. However, there is no accurate information about the installation location of facilities, so their utilization is often poor [4]. To maximize the utilization of this information, each fire station conducts a survey on the status of firefighting facilities for specific fire target buildings within the jurisdiction at regular intervals and records a survey of the relevant physical factors that are necessary for firefighting tasks. They conduct data surveys that are necessary for firefighting facilities such as evacuation facilities and hazardous materials facilities. However, since these fire activity information cards are based on paper documents, the location data for each installed facility in a building cannot be identified by the facility manager or confirmed directly at the fire site.

Expert interview on the current system limitations

Facility managers and fire brigades were interviewed to assess the limitations of the current fire response system. The facility managers explained why the utilization of firefighting facilities installed in buildings is inevitably low for buildings' current fire response systems. Related laws for disaster safety management are increasingly strengthened, but existing buildings use aged facilities that are limited in their application of the latest laws. Furthermore, since such buildings are limited to buildings of a certain size, existing small- and medium-sized buildings are vulnerable to fire. The biggest problems for rescue teams when firefighting in current buildings is the inconsistencies between provided drawings and actual buildings and the absence of location data on fire ignition and related facilities.

To improve the effectiveness of existing fire response systems, rescue teams should be able to identify the latest building information and related location information. To support this, the facility managers should be provided with an information management system that can store information required in fire response in advance and continuously update it [12]. In addition, information should be systematically managed in emergency situations so that reliable information can be immediately transmitted to rescue teams. This is required to secure the quality of each data set for reliable information, and data standardization should be performed to enhance the quality management of information [13]. The absence of data standards hinders effective information flow among emergency responders. Therefore, the management information of the building and facilities that can be used in fire sites should be prepared in advance and data structures are required to organize system database construction.

3. Data structure for building fire response

As predicting building fires is difficult, building information management based on location data is required in terms of fire prevention and response. Previous research results on the development of building information management systems are being published. The demand for IT technology is increasing as the role of collecting and analyzing various aspects of data. In addition, the combination of computer technology and fire safety management has become a trend. As described above, information-based decision making is a critical factor at fire sites, but direct access to information to assist rescue teams in situation awareness is vulnerable. In particular, sharing indoor information required for search and rescue is insufficient and lacks objective and quantitative data, which makes decisions difficult [14]. The quality assurance of data collection should be considered in building fire sites because facility managers and rescue teams should be able to communicate accurate and reliable information in minimal time. Therefore, data standardization should be the first priority and data classification is the most basic problem to be solved for information management. Vimala nunavath et al. [2] what information was required for on-site control during search and rescue on a campus and indicated identified items as a useful tool for communicating with end users using the UML model. Nan Li et al. [3] categorized the information requirements before and after the arrival of a rescue team using the scenario methodology. Through a one-on-one interview with the rescue team, the card game method can be used in which the rescue team becomes a virtual player and derives necessary data according to the response process. Rui et al. [15] presented a data model that could be used in fire response from a business perspective. This data model has established a comprehensive information standard classification system for fire response by accessing activities according to on-site and off-site rescue response processes. Bae and Park [16] derived five management for safety management in the underground space and analyzed the fire risk assessment weights for each detail.

All of the above studies emphasized the necessity of information requirements for facility managers and rescue teams and made efforts to standardize the data structure for what information can be utilized in fire responses. They contributed to the classification of required information according to the user in the fire response. However, as there are overlapping items in a large category of required information between facility managers and rescue teams, additional alternatives to integrated information management are required that can be used either directly or indirectly. In other words, it is somewhat difficult to apply the integrated system in terms of data sharing and data management because the items have been changed according to the method of conducting the research or the users and this is classified without reflecting the linkage of information between emergency responders. As a preliminary step for developing a system database, this paper re-classifies the required information of emergency responders derived from previous studies and reconstructs information that can be provided easily and intuitively in a single-system environment such as BIM according to the response process.

3.1. Integrated Data structure for emergency responders

Various data models have been proposed to solve the lack of information in the building fire response. It is necessary to redefine the data structure because the approaches and interpretations differ according to the building type and the end user of information. These proposed information requirements are extracted from the classification proposed by previous studies. Based on the extracted information, they are redefined into items that allow users to maintain a database easily in the system environment to be developed. As depicted in Figure 1, there are 18 items that were mentioned repeatedly in previous studies, including general information about the building, information about the inside of the building, installed facilities and equipment, and real-time fire information. In the building fire response, users' information requirements can be divided into "Pre-gathering data" and "Real-time gathered data." Pre-gathering data is reclassified into five categories, which can be managed in advance: general building information, building space information, fire risk element, available resources in the fire, and maintenance history. Real-time gathered data should be collected and analyzed in real time after a building fire; it is divided into two categories: real-time fire/smoke condition and occupant information. This paper only defines the data structure for the pre-gathering data, which is a data structuring step in which the above information is computerized in advance and utilized as an information support system in the building fire response through continuous data management.

As depicted in Figure 2, it is divided into physical information and management information aspects depending on the data characteristics. In particular, the indoor space element, fire risk element, and available resource element could be managed as a three-dimensional object according to the fire response process during the implementation of BFIMS as proposed in future research.

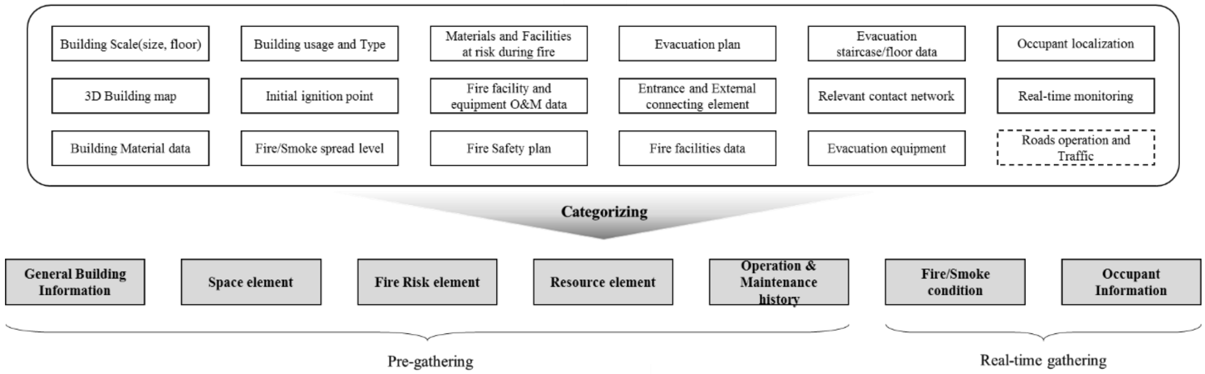

Figure 2. Categorizing data from literature reviews

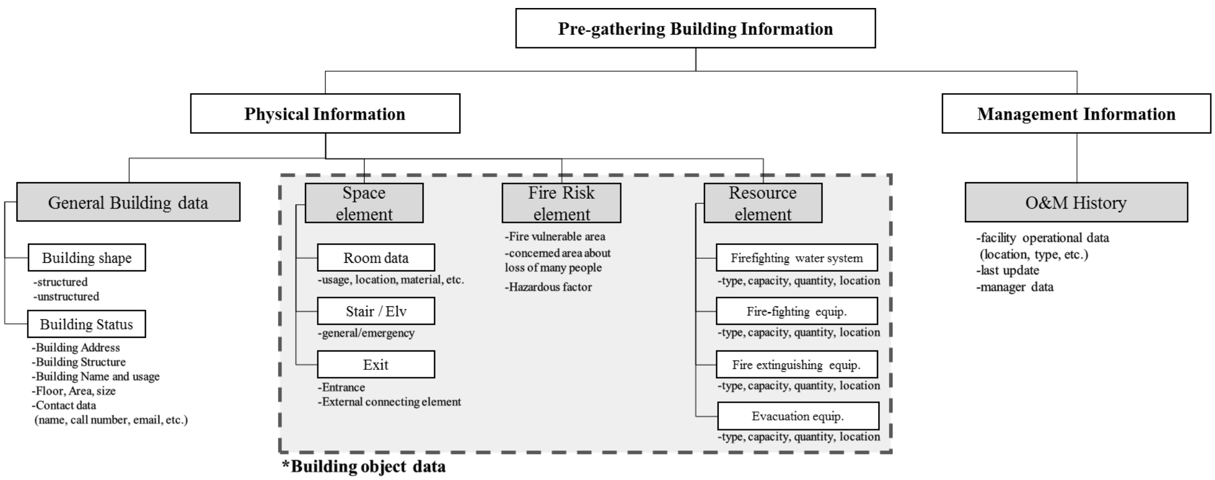

Figure 1. General elements breakdown of Pre-gathering data for building fire response

4. Conceptual Data model suggestions for System development

BIMs are a useful tool for storing a vast amount of information and can be used as an integrated information system for indoor spaces. Most of the current BIM studies in the field of building fire-disaster management are used for rescue and evacuation route analysis or fire simulation analysis that take specific factors into account. Wang et al [10] proposed a BIM-based integrated system that consisted of four modules: evacuation analysis and evaluation, evacuation route planning, safety education, and equipment maintenance. The proposed system could analyze fire safety in conjunction with FDS simulation and store information that supports safety management in a web-based environment. Cheng et al [17] conducted a study on an integrated system that could be used continuously in fire prevention and response using BIM and a wireless sensor network. The system displays fire status and occupants' location information on the screen through monitoring and provides two-way route guidance between occupants and rescuers through mobile interlocking and an LED guiding device. Although the above studies have attempted to develop a system with functions such as real-time data acquisition, occupant tracking, and device and equipment management, essential information such as firefighting facilities remains incompletely reflected. Moreover, BIM is used as a platform for visualization, or as a study for convergence with other software. The utilization of spatial information, which is BIM's biggest advantage, is poor. In addition, an integrated management system for fire disaster management is only effective for extracting relevant information rather than operating all BIM information created during a building lifecycle.

This study proposes an integrated classification scheme for information that is commonly required by emergency responders based on the data structure described in Section 3 and defines a user-centric data relationship so that database management is easy based on the derived information requirements. In future studies, a prototype of BFIMS should be developed using BIM. The first thing to do when designing a system database based on user-required information is defining the DB information requirements (see Table 1). For example, a fire extinguishing facility could be modeled as an object on the system in the resource element of the building object data among the physical information of the pre-gathering data, and the related location, types, and quantities could be expressed in the building modeling. Information requirements could be configured as attribute data according to each class and the relationship between items can be defined.

Table 1. DB Definition of pre-gathering data requirements from data breakdown

Level1	Level2	Level3	Definition description	Example
Physical information	General building data	Building elements	Building outline composed of structure and non-structure	Structures: slabs, walls, columns, etc. Non-structure: doors, window, stairs, etc.
		Building status	Building status; General information without forms	Building name, address, main usage, building structure and scale(floors, area), contacts network
	Building Object data	Space element	Spatial data	Room's usage, location, materials
			Vertical flow data	Location of general stairs and elevator, escalator, emergency stairs and elevator
			Externally connected elements	Main entrance, exits, rooftop, and external connection zone.
		Fire Risk element	Facility/Area to be checked and responded to in case of a fire event	Locations and impacts of fire-vulnerable areas, hazardous materials, and facilities' location, type, and quantity
		Resource element	Fire extinguishing equipment	Location and status (type and quantity) of indoor/outdoor fire hydrants, fire extinguishers, etc.
			Firefighting activity equipment	Location and status (type and quantity) of connection sprinkling facilities, connection water pipe facilities, etc.
			Firefighting water equipment	Location, capacity, quantity, and type
			Evacuation and rescue equipment	Location and status (type and quantity) of evacuation equipment (evacuation ladders, rescue lifts, etc.) and lifesaving equipment (air respirators, heat shields, etc.)
Management information	O&M history		Maintenance history of physical information	Responsible members' data, latest update data, and whether the facility is operational.

When a data model has been constructed, the platform on which the system will run is selected. The platform determines the system complexity based on plug-ins, user access, and user capability. It should be easy to modify the changes and construct the database. In essence, it is important to set the level of information that can be handled by the user when accessing the system. In general, for facility managers, the system interface and how it works should be simple and easily mastered. In this study, a Sketchup API would be chosen as an alternative. Sketchup is modeling software that has a simple user interface and can configure program add-ons by user's convenience with extensions (called plug-ins). This enables extensions to BIM and 3D modeling. Industry Foundation Classes (IFCs) are an international standard for BIM object libraries developed for data exchange in the AEC industry. Using an IFC model enables interoperability among the various systems that support the IFC format and this can be broadly extended depending on the purpose of development.

In building fire data management, BIM-based systems using IFCs for systematic fire information management systems can design data models that are specialized for fire safety management. A conceptual data model was designed to propose a data structure of BFIMS. This represents the class and data relationship definition. Figure 3 shows the entity relationship focusing on firefighting equipment that is available in building fire response. *IfcObject* consists of an *IfcElement* that represents building shape and an *IfcSpacitalStructureElement* that stores the building general information. The information requirements related building fire response is dependent on *IfcInventory* class and stores physical and management information. For example, fire hydrant information provides physical information such as type, connection size, and intrinsic characteristics. It includes simple inventory data about simple management information. The information management items to be added according to the user's purpose can be stored and managed in *IfcPropertySingleValue*.

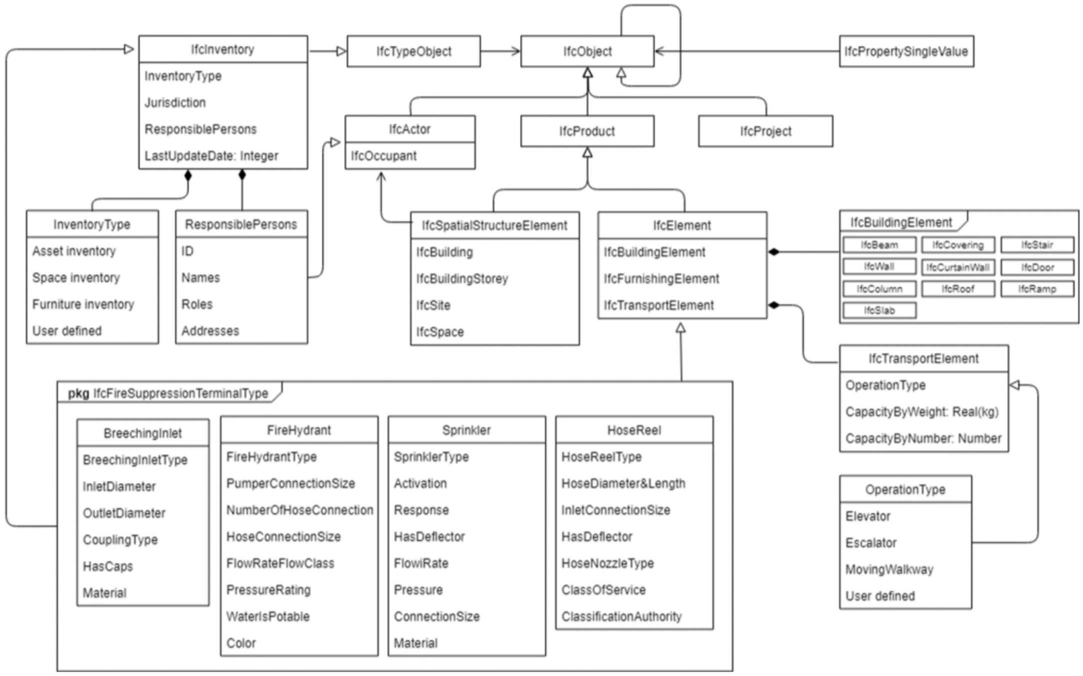

Figure 3. Conceptual IFC data model about predefined Fire Suppression Terminal Type

Figure 4 shows how facility managers and rescue teams can utilize the proposed system in actual situations. Facility managers can acquire detailed information and the inspection history of related fire facilities based on the object data stored in the proposed BFIMS. They also keep their buildings up to date and perform daily monitoring work by reflecting changes when the indoor elements or objects change. When a fire occurs, the system alerts facility managers and provides them with fire-related information such as object's location and attribute data through 3D visualization. Meanwhile, they can grant system access privileges to rescue teams so that they can share information and the rescue team collects relevant information in advance through a shared view when they are dispatched. This supports the establishment of the optimal response strategy by sharing the indoor information that is required in building fires. If BFIMS and intelligent sensors can be combined, it would improve the speed of real-time information collection.

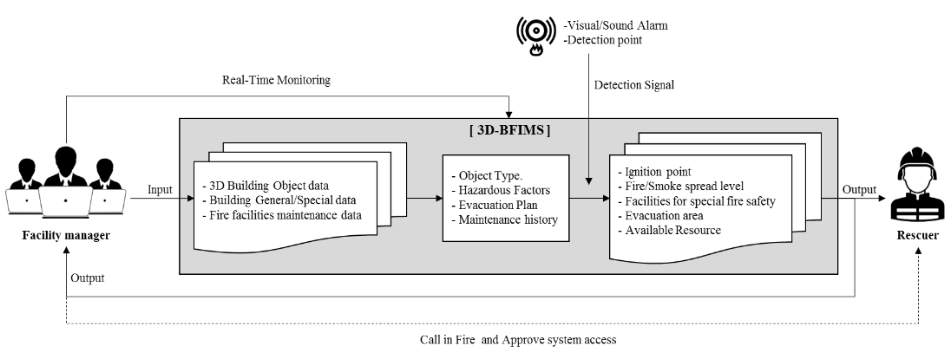

Figure 4. System operation framework

5. Conclusion

In coping effectively with building fires, the issue of how to support and respond at a fire site quickly and accurately plays an important role in the early stages of fire occurrence. Emergency responders such as facility managers and rescue teams should be made aware of the correct situation quickly and make optimal decisions using all distributed information that is generated at the fire site. The current building fire response method does not provide rescue teams with the latest information about the building, so the accuracy is low and collecting the required information takes time. Previous studies have sought to obtain the information required for emergency responders and to ensure the reliability and accuracy of the information gathered during the building fire response using 3D modeling tools such as BIM. However, this is often confined to the technical side and the interpretation can differ depending on the approach.

This paper proposes integrated information requirements for emergency responders by recognizing that appropriate information should be shared among emergency responders in the building fire response. Based on the proposed data structure, a direction was suggested for the development of a 3D building fire information management system (BFIMS). This contributes partly to the field of building fire safety management by suggesting a data structure that includes object-based indoor facility information for effective building fire response. It can also help improve the information usability of the fire response by suggesting a user-centric data structure. It is meaningful that 3D modeling using the proposed data structure can supplement the limitation in the utilization of indoor object information and provide more detailed and intuitive information related to indoor fires. Therefore, it supports the decision making of emergency responders by sharing as much spatial and indoor object information as is required in building fires. Therefore, the initial response speed could be improved, thus contributing practically by improving the building fire responsiveness. In future research, we will develop a system prototype by supplementing the proposed data model and system functions and apply it to actual buildings to verify its effectiveness and efficiency.

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A Synopsis Of 3D Printing And Robotics Applications In Construction

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Abstract

One of the difficulties hindering the application of 3D printing technology in construction is related to the versatility of materials and components used to produce a building or other structure. The prospect of using this technology is further complicated by the sheer size of the edifices to be constructed. While 3D printing a mechanical component can now be done in someone's basement with affordable and readily available equipment, applying the same technology to produce large structures and building components is a challenge. In recent years, researchers have been working towards overcoming this challenge by trying to develop new construction materials and methods that would be more suitable for the application of 3D printing technology. One of the approaches that can be considered is the combination of robotics technology with 3D printing to automate construction activities. The use of robots in construction has been proposed long before 3D printing became possible or known but never gained widespread construction site usage, mainly because of the difficulty associated with the automation of most construction tasks. However, the combination of 3D printing with robotics may be the way to change that. In this paper, the authors examine the suitability of 3D printing in a number of construction tasks and present ideas that modify established construction methods to make them more suitable for automation. The authors then examine how the introduction of robotics in conjunction with 3D printing to the construction site may make it possible to automate a number of construction tasks. Some of the benefits of such automation include lower safety risks, improved control over construction schedules, more economical construction, and a better ability to build in remote areas and challenging environments.

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Keywords: 3d printing, construction automation, construction technology, robotics;

1. Introduction

Back in 1986, Whittaker [1] described construction robotics as an "infant discipline whose mature form is not apparent." More than thirty years later, this statement still holds true in spite of significant advancements in computer and automation technologies. Although robots have been quite successfully used for decades in areas such as manufacturing, commerce, space, and marine exploration, and other fields, their use in construction has not been as widespread as many in the industry would have wanted it to be. This is by no means due to the lack of foresight or effort on the part of researchers and professionals in the industry. In fact, the idea of incorporating automation in the construction process has been floating around for a long time and may have started even before researchers such as the

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ones referenced in this paper started reporting on it. Garbotz [2] investigated the needs in capital for shifting manual work to machines in order to increase productivity and was among the first researchers to address the issue of automation in the construction industry. Klein and Patterson [3] studied the possible use of multiple-armed robots in the construction of large space structures, and they described a successful effort to simulate the locomotion of a vehicle with arms that was modeled after currently (1982) available industrial manipulators. Hasegawa [4] reported that the first appearance of building construction robots in Japan took place in the mid-1970's and mentioned six pioneering research projects that were carried out between 1978 and 1979. These projects investigated the automation of activities such as wooden panel wall assembly, tall building surface panel assembly, and other operations. Hasegawa [4] reiterated the need for developing new robot engineering technology for the construction industry and went on to propose a conceptual design of a robotized construction system, which represented the basic idea of today's 3D printing technology. Hasegawa [4] concluded that, in order to accomplish the desired automation, a large task force with sufficient financial support and time will be needed to successfully study all the required development topics.

In a book that was published in 1988, Yates [5] predicted that, by the turn of the twentieth century, there was good potential for increased use of self-directed robots controlled by expert systems. At the time, some automation and robotics technology was already being used to finish concrete, spray-paint buildings, or carry out certain tasks in hazardous environments. Drazan [6], one of the early researchers who investigated the use of robots in the construction industry, divided the potential robotics application areas in construction into three groups, which include the automation of existing equipment, the automation of existing processes, and the use of robots for existing manual processes. These proposed approaches might have worked for some aspects of the construction industry including tunneling and excavation, prefabricated and modular construction, and, more recently, moderately applicable 3D printing. However, they nonetheless proved to be insufficient for bringing significant automation to this considerable sector of the global economy. Balaguer [7] argued that the main difficulty with robotics and automation in construction (RAC) is related to the unstructured nature of construction sites and a number of other issues, which will be discussed in the next section. Balaguer [7] went on to state that there are two types of robotics interventions that can be applied to RAC: hard robotics and soft robotics. In hard robotics, robots are designed to directly automate construction processes. In contrast, soft robotics research aims at integrating software with on-site sensory data acquisition and processing, human operator's safety and security, and chip-based process control among other robotic and automation hardware. Louis et al. [8] weighed in on the reasons behind the contrast between the levels of automation in the various manufacturing industries compared to that in the construction industry. They attributed the disparity to the distinctive nature of construction activities, which are characterized by "customized projects, uncontrolled outdoor work sites, and necessary collaboration between disparate entities." They also noted how the lack of progress of real automation in the industry led to a decline in construction robotics research activities. They cited the findings of Son et al. [9] who studied global trends in research and development of automation and robotics in construction and reported that the percentage of papers categorized under "Construction Robotics" declined from 71% in 1990 to 33% in 2008. Louis et al. [8] came to the conclusion that the issue of automation of construction needs a fresh examination in order to fulfil the vision of a fully automated construction worksite. They went on to describe a new approach that enables the automation of entire construction operations by using Discrete Event Simulation (DES) models to orchestrate and actuate robots on the construction site.

Based on this discussion, it is clear that the solution to the construction automation problem needs to go well beyond the automation of existing processes. The construction industry has a lot to gain from integrating more automation in the construction process. Such automation will generate a number of improvements, including faster and more efficient construction methods and processes with better results in terms of safety, quality, and cost. In this paper, the authors first consider some of the challenges that the construction industry has been facing in its effort to incorporate more automation. They then propose an eight-step process in which robotics and 3D printing in combination with innovative materials and methods of construction can be used to achieve a sustained automation effort.

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2. Drivers for and Challenges to Construction Automation

It is well established that the construction industry, with a few exceptions, is generally on the slower side when it comes to adopting automation technology. Exceptions to this general observation include the prefabricated and modular construction and the steel fabrication sectors, which have significantly benefited from advances in automation and robotic technologies. In other words, automation primarily benefited all construction related activities that can take place in a controlled, manufacturing-like environment. For most remaining sectors of the industry, construction means and methods have seen little change over time. This is not to say that the industry can afford to continue along this path. Banik and Barnes [10] identified a number of challenges that the construction industry is facing, with the first issue having to deal with an anticipated shortage in resources, including skilled workers and technical and supervisory staff. This would be a major problem that automation can readily solve. Owen et al. [11] suggested that the continued practice of using paper specifications and drawings to define the technical requirements and configurations for construction products does not facilitate the integration of physical work processes. As a result, they maintain that opportunities for making use of appropriate levels of automation are largely lost. This is because this traditional method of design information production and delivery does not promote during the design process the consideration of detailed fabrication and assembly or the best venue for performing certain construction tasks.

Feng et al. [12] identified the rugged, dynamic, and unstructured environment of the construction worksite as well as the uncertainty and evolving sequence of on-site events as unique challenges that stand in the way of widespread use of robotics and soft automation in construction. They noted that the challenge for the robotics industry that wants to cater to the construction sector is to design and build robots that are capable of sensing and adapting to environmental changes, in addition to the ability to replicate basic human motion. Elattar [13] who studied opportunities for automation and robotics in construction stated that one of the challenges that the construction industry will face in the next few decades will be to meet the demand that will result from enormous migration to cities. He cited forecasts indicating the ratio of urban population in the world will go from 45% in 1995 to 55% in 2015. According to data obtained from the World Bank Web Site [14], Elattar's [13] prediction was quite accurate as urban populations around the world increased from about 45% in 1995 to about 54% in 2015 and reaching nearly 55% in 2017. Elattar [13] argued that automation will play a big role in helping the industry meet the increased demand and identified many areas where automation has been tried.

According to Gagliordi [15], Autodesk also weighed in on the population issue by focusing on its global rise, which will lead to increased demand for buildings. This demand, combined with the short supply of qualified workers create a need to change the traditional construction techniques. Autodesk's solution to this problem is a sort of a portable additive manufacturing "toolbox" for the construction industry. The idea is to package various robots and printing systems capable of printing large components in shipping containers and to send them from one job site to another as needed. According to Gagliordi [15], this method could be a solution to the construction labor shortage problem and would enable parts to be produced faster and more accurately. To summarize, it is evident that the idea of fully automating construction processes faces many challenges that the industry has so far not been able to resolve. The uniqueness of each project combined with the variability and rugged nature of construction sites make it unwelcoming to robots, which are best suited to operate in predictable and organized environments. The variability in construction components and their materials, different components that often may need to be installed at the same location within the same timeframe, adds another dimension to the already challenging task of developing viable automation processes. The variation in construction methods between trades and the possibility of them having to operate concurrently creates the need for having multiple robots operating within close proximity from each other. Having machines around the construction site that may make sudden unpredictable moves creates a safety hazard. Also, weather and other environmental factors can have an adverse effect on the performance of robots. And finally the use of robots may present some unique liability issues that need to be investigated and dealt with. For example, when a robot's malfunction causes a project delay or an accident, it may not be very clear if the responsibility should be assumed by contractors, designers, the owner, or the robot's manufacturer or programmer. One can only imagine the ramifications of a situation where a robot causes an accident because it made a wrong decision when its visual analysis system became impaired by a sudden poor weather condition. However, it may be possible to avoid weather related issues in some projects. For example, Kim et al. [16] proposed a conceptual model for what they called a construction factory (CF) which is a temporary structure that will shield robots from weather and environmental elements during construction.

3. Automation and Robotics

Robots can be defined as high performing computer systems that are motion capable and that can be programmed to perform tasks that normally can only be performed by humans. When the tasks to be performed are simple, the robot can consist of a number of mechanical parts that are driven by a simple sequential computer code. This includes, for example, simple repetitive actions such as moving certain objects from one specific location to another, or continuously depositing welding material between prepositioned parts. However, robots with specialized capabilities and Artificial Intelligence (AI) driven software are typically needed to carry out tasks that go beyond simple predefined motion. To put this into perspective imagine that a robot is to assist with the construction of a reinforced masonry wall. The robot's task is to alternate between positioning a course of Concrete Masonry Units (CMU) in place and then following up with the positioning of reinforcing steel. One of the challenges here for the robot is to recognize what it is picking up so it applies the appropriate amount of force to the object without crushing it (too much force) or dropping it (too little force). Moreover, to be able to pick up components and place them where they belong, at a minimum, a robot needs to have the ability to 1) know the item's original location, 2) have a mechanism to safely pick up the item, 3) know the planned item's position, 4) have a mechanism to safely manipulate the item into its final position, and 5) have the ability to adequately attach the item while holding it into place. These minimum requirements will allow the robot to install the item but do not address other important requirements, such as safety for example: robots will also need to have the ability to identify hazards and avoid them. The ability to identify an object and know how to deal with it must rely on sensory attributes that come naturally to people but that robots must be designed to have. To be effective in the construction site, robots need to be aware of their surroundings at every moment and need to be able to recognize objects by relying on technology such as image recognition, radar, laser, and GPS. Luckily for the construction industry, these technologies have been well developed for the automotive and other industries in recent years.

Ardiny et al. [17] conducted a comprehensive review of state-of-the-art research in automated construction by autonomous mobile robots. They identified three general categories of construction robots: tele-operated systems, programmable construction machines, and intelligent systems. Tele-operated systems are machines that are remotely controlled by human operators who interpret data and cognitive activities. Programmable construction machines can be pre-programmed to perform a number of functions that a human operator can access through a menu and direct the machine to execute them. The intelligent systems category encompasses machines that can accomplish tasks in fully autonomous mode (with no human intervention) or semi-autonomous mode (with some level of human interaction). Ardiny et al. [17] concluded that there is a need for more rigorous research related to hazard detection, accurate positioning, human-machine and machine-machine interaction and collaboration, and the development of new materials, components and processes that are more suitable for automation.

4. Robotics Automation and 3D Printing

The solution that will lead to meaningful automation in the construction industry must go beyond 3D printing and automating typical construction methods. This is because construction means and methods that were developed around peoples' abilities are not necessarily the best suited for automation. For any effort to be successful in effecting more automation in the construction industry, it must first include an evaluation of the adaptability of prevalent practices to automation, and then it must look into developing new construction methods and materials be able to take full advantage of all the automation technologies that may be available today or in the future. The illustration in Fig. 1 shows a simplistic classification of construction tasks based on their adaptability to automation. Prefabricated components are constructed in volume in a controlled manufacturing environment, typically using a repetitive process. This makes them a prime candidate for automation.

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Fig.1. Classification of Construction Tasks Based on their Adaptability to Automation

Next on the list are shop fabricated components. These may include structural steel members and trusses, wood trusses, and HVAC and other similar components that are specifically designed for a project and that can be fabricated in a controlled shop environment by stationary robots. In general, automation has been quite successful in these two categories of construction. The third category in order of increasing difficulty of automation includes the placement of finishes such as painting and placing fireproofing on exposed steel members. These types of activities have the advantage of being well defined in space, but their automation requires the use of robots that are capable of motion. This adds a safety concern and a new dimension to the automation effort as robots that are intended to be able to move must also have the ability to be aware of their surroundings in order for them to avoid hazards.

Partially fabricated systems are those that consist of assemblies of prefabricated or shop fabricated components. For example, steel frames that are made up of assemblies of shop fabricated beams and columns belong to this category. The challenge, in this case, is how to automate the process of lifting the prefabricated or shop fabricated components and attaching them in place. The specialty trades category encompasses all construction activities that deal with electrical, plumbing, mechanical and similar systems, and involving activities that often must be accomplished in confined spaces with many interferences and using special equipment. The ability to achieve satisfactory automation of these activities will require a considerable research and development effort to formulate novel means and methods that are more amenable to automation. The key to achieving a complete and successful automation in construction is to invest in significant research leading to the development of new technologies and construction materials and methods that will help the automation effort to move forward. The construction site of the future could very much look like one where 3D printers and different types of robots work in synch to complete a construction project.

3D printing is a different name for what has been known in the manufacturing sector as additive manufacturing. The process works by having a computer controlled system superimpose layers of material to form a shape for which the geometry is defined by a three-dimensional computer model. There are clear limitations to this process as, for example, it cannot span between parts of the object being printed because there is no material to add to. When the object to be printed is small, a filler material can be used to act as temporary support for the spanning portion of the object and then removed when the object becomes able to support itself. However, this approach will not work well with large building structures. The alternative becomes to prefabricate spanning elements and use robots to install them or to provide temporary support by some other means so the 3D printing can be performed. Specialized robots may also be used to perform tasks such as welding, bolting, painting, or even a combination of tasks. Moreover, new construction methods and processes will need to be developed. For example, large-scale multi-arm robots can be used for the erection of structural steel. This will require some revisions in the methods of fabrication and preparation for erection of structural steel components. An adequately designed robot should be able to pick up a component in its proper sequence of installation and hold it perfectly in place with one arm while other arms weld it or bolt it to its supporting member. This will allow for structural steel members to be erected faster and with more accuracy than if traditional methods are used. For this to work perfectly, changes will need to be introduced to the fabrication process as well to produce structural steel components that can communicate to the robot information about what they are and their sequence of installation. Evidently, the information needs to be finalized during the design process so it can be forwarded to the fabricator along with fabrication details. This reinforces the idea that the success of the automation effort in the

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construction industry will require more than just trying to automate current construction practices. The automation process needs to start during the design phase with sophisticated Building Information Modeling (BIM) models that capture each little detail of the project. There are many areas where construction means and methods need to be reinvented for successful automation and one more example that the authors wish to present in this paper has to do with the construction of reinforced concrete members. If one is to consider the construction of a reinforced concrete beam, the traditional method is to assemble the reinforcing steel bars and stirrups in the shop or on site, construct the formwork, and place the reinforcing steel in the forms in such a way that it lines up adequately with the reinforcement of other connecting members. Once workers verify that the reinforcement is placed in such a way that concrete cover requirements are met, the concrete pouring process can be initiated to complete the beam. This intricate process is clearly not suitable for automation. However, with some modifications that take into consideration the accuracy that can be achieved from concrete 3D printing and the advanced capabilities of current robots, it becomes possible to automate the construction of a reinforced concrete beam by following a different process.

In this regard, the authors wish to introduce an eight-step process for the automatic construction of reinforced concrete members. The proposed process assumes that the supporting columns have already been 3D-printed leaving room for continuing reinforcement to be doweled in. Since the 3D-printing process is achieved by adding layers of material that hold their shape, only a platform will need to be constructed to support the beam during construction. This will save the effort of having to build a complete set of formwork for the beam. Once the platform is in place, the portion of concrete just below the main bottom reinforcing steel is 3D-printed, leaving an empty space for the rebar that will eventually be inserted into the column. At this point, a picking and placing robot places the preassembled bottom reinforcing steel in place. In this step, the bars are connected together at only a number of points to make it easy for the robot to pick them up and position them accurately. Next, the part of the beam between the bottom and top reinforcements is 3D printed. When additional longitudinal reinforcement is required anywhere in the beam, it is simply placed by the picking and placing robot when the 3D-printing reaches the appropriate elevation. The 3D-printing process in this case leaves open areas in the beam to allow for shear reinforcement, top vertical reinforcement, and column rebar or continuation dowels to be inserted. The next phase involves the placement of the top reinforcing bars and the shear reinforcement stirrups by the picking and placing robot. In this step, the shear reinforcement stirrups are inverted U-shaped pieces of steel that a robot can easily drop into the space that was left empty, in order, and using the design specified spacing. Following this, the 3D-printing robot uses a special bonding compound to fill the space that was initially left empty and now is partially occupied with stirrups. The nature and composition of the bonding compound is something that will need to be investigated by the concrete materials research community. The final stage of the beam construction process would be for the portion of concrete above the top reinforcement to be 3D-printed.

5. Conclusions

The world is facing many infrastructure challenges that need to be readily addressed and the construction industry must position itself to meet those challenges. Faced with a shrinking labor force and the requirement to execute more complicated projects with increasingly limited resources, the industry has to intensify its effort towards significantly incorporating more automation into its processes. The computer information and robotic technologies have come a long way in the last few years and there are many advanced technological tools available today that can be used by the construction industry to improve and automate its processes in all of its sectors. However, significant construction automation research needs to be done to achieve this objective because the difficulties that are associated with this endeavor are very unique and specific to construction, and many of the automation techniques that have been working well for other industries are just not suitable for automating most construction activities. In this paper, the authors made the case for the need of a rigorous research effort in construction materials and construction means and methods to be able to take full advantage of robotics and 3D-printing technologies. It must also be pointed out that a successful automation of construction activities will not be achieved if construction methods are not considered during the design process. Building information models must be expanded to include detailed construction related information, and a platform for integrating Building Information Modeling (BIM) with Construction Information Modeling (CIM) must be created.

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Allocating BIM Service Cost—A Taiwan Experience

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Abstract

Benefits of BIM application in building construction projects have been reported by many previous researchers, but very few works were done for the guideline of estimating and allocating of the costs of various BIM uses. Without such a guideline, it is difficult for the owner to determine and budget the selected BIM uses. To meet this need, this paper presents a case study on the estimating and allocating the costs of BIM service based on the 25 BIM Uses defined in the 'Taiwan BIM Guide' developed by the Architecture and Building Research Institute (ABRI), Ministry of the Interior (MOI), Taiwan, for implementation of BIM by local construction industry. Appropriate portfolio of BIM Uses should consider the limitation of available resources and specific project characteristics. Only the priority of the 25 BIM Uses need to be selected and budgeted. To estimate and allocate required costs for various BIM uses, the current study proposes a method to determine the relative requirements of costs for different BIM uses by surveying the BIM practitioners from the 10 public social housing projects owned by the Taoyuan City Government using an Analytic Hierarchy Process (AHP) method. A BIM use cost allocation guideline is provided as a reference to the BIM practitioners to determine the required costs for different BIM Uses.

Keywords: Building Information Modeling (BIM); BIM Guide; BIM Use; BIM service cost; Analytic Hierarchy Process (AHP).

1. Introduction

In the past few years, many Building Information Modelling (BIM) implementation guides have been developed by the government agencies or professional associations in many countries, such as the 'BIM Project Execution Planning Guide (PEPG)' by CIC [1] and the 'National BIM Standard-United States' by NIBS [2] in the USA, the 'Publicly Available Specifications (PAS) 1192-2 [3]& 3[4]' by BSI in the UK, the 'Singapore BIM Guide' by BCA in Singapore, the 'Unified Standard for Building Information Model Application' by General Administration of Quality Supervision [6] and 'Shanghai BIM Guide' by Shanghai City Government [7] in China, and the 'Taiwan BIM Guide' by ABRI [8] of Ministry of the Interior in Taiwan. The BIM Guides of different countries are usually developed according to the specific construction characteristics and local industrial requirements. As a result, they provide specific purpose to fit the local construction environment and specify different requirements for BIM project delivery.

Although the BIM Guide provides the participants a clearer specification to deliver, review and accept the project deliverables, there are two problems remains to be resolved before the BIM Guide can assist the construction industry to implement BIM adoption: (1) How to select the most appropriate BIM uses for a specific project? —since the project

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characteristics, the project delivery method, and the owner's needs may differ from one project to the other, only the most appropriate BIM uses should be adopted; (2) How to budget the selected BIM uses?—different BIM uses will cost the efforts of the BIM service provider differently, it is desired to estimate the cost borne for the selected BIM use items. Although previous researchers have found that the adoption of BIM will reduce overall project cost [9] and thus most BIM service providers will bear the costs of BIM adoption [10], it is the common practice for the project owners (especially the public project owner) of the BIM developing countries to offer inceptives or subsidy for BIM services in the early phase of BIM introduction in order to encourage the BIM adoption by the industry [11,12,13]. Moreover, the decision of the second problem may further affect the decision of the first problem, since the project owner usually allow limited budget for BIM services. As a result, the correct estimation of BIM service costs for various BIM use items is very desirable, not only for budgeting the costs but also for progress payment of BIM services.

In light of the abovementioned objectives, the current research aims at proposes a method to determine the relative requirements of costs for different BIM uses by surveying the BIM practitioners from the 10 public social housing projects owned by the Taoyuan City Government using an Analytic Hierarchy Process (AHP) method. A BIM use cost allocation guideline is provided as a reference to the BIM practitioners to determine the required costs for different BIM Uses.

2. Relevant Works

2.1. BIM Uses defined in this research

As addressed in the Introduction, the costs of BIM services specified by different BIM guide will bear different costs, it is necessary to define the BIM uses clearly before the BIM service costs can be correctly estimated. In this research, the BIM service costs for the 25 BIM uses defined in 'Taiwan BIM Guide' are selected for case study. The 25 BIM uses defined in 'Taiwan BIM Guide' are defined and described in this subsection. The BIM use items of Table 1 are the outcomes generated from the BIM model developed by project participants in the stage of the project. For example, '(8) Construction permit' means the use of Basic Design BIM Model to produce the drawings required for application of 'Construction permit'; similarly, '(15) Budgeting' means the use of Detail Design BIM Model to generate required bill of quantity (BOQ) for budgeting; and so forth.

2.2. Analytic Hierarchical Process (AHP) and Adaptive AHP Approach (A^3)

The Analytic Hierarchy Process (AHP) method was originally proposed by Saaty [15], and it has been become a widely adopted tool for multi-criterion decision making nowadays [16]. The AHP procedure consists of six general phases or steps [15,17]: (1) Define the decision problem; (2) Construct the decision hierarchy; (3) Construct matrices to calculate a set of pairwise comparison; (4) Calculate the relative weight of the elements to each level; (5) Check and balance of decision; and (6) Decision documentation. It has been applied to multi-criterion decision making in many fields, including Information Technology [18], Public Administration [19], Manufacturing [20], Transportation Industry [21], Service Industry [22], etc.

Although AHP provides a useful method, there are several weaknesses of the traditional AHP in assessing the relative importance weights as pointed out by Triantaphyllou and Mann [23] and Lakoff [24] due to the use of Saaty's discrete 9-value scale to reflect the decision maker's preferences and the human's difficulty in identifying the in-between preference scales. These are sources of the high Consistency Ratio (CR) defined by Saaty [15], i.e. high inconsistency, while applying AHP method.

In order to improve these drawbacks, Yu [25] and Lin et al. [26] proposes an Adaptive AHP Approach (A^3) using simple Genetic Algorithms (sGA) to recover the real number weightings of the various criteria in AHP and provide a function to improve the consistency ratio of the pairwise comparison automatically. The A^3 also eliminates the tedious reassessment process when the consistency ratio is slightly unsatisfactory. It is very desirable for decision-making problems, as the interviewees of AHP are usually high-ranked manager or domain experts who are extremely busy and are not available for iterative re-assessment of the pairwise comparison matrixes. Details of the A^3 can be found in Yu [25] and Lin et al. [26]. In this paper, the original A^3 program is adopted for fine-tuning the relative weightings of criteria in AHP.

Table 1. The 25 BIM uses defined in 'Taiwan BIM Guide' [14].

Stage	Objective	Description of objective	BIM Use Item
Planning	Mass planning of the building	Showing rough length, area, volume, position and orientation of building.	1.BIM execution plan (BEP) 2.Site analysis 3.Conceptual design 4.Final conceptual model
Basic design	Schematic building components and systems	Showing qualitative and quantitative schematic information of building.	5.Basic architectural design 6.Basic engineering design 7.Basic design estimate 8.Construction permit 9.Final basic design model
Detail design	Building component and system development	Showing accurate qualitative and quantitative information of building components and systems.	10.Detail arch. design 11.Detail structural design 12.Detail MEP design 13.Detail design estimate 14.Detail design integration 15.Budgeting 16.Final detail design model
Construction	Model to support construction management designs	Providing required information for construction, prefabrication and installation; 2D construction drawings.	17.Construction model 18.Pre-construction planning 19.Construction drawing 20.Change order 21.Occupation permit 22.Final construction model
Completion	As-built model	Ensuring correct and accurate qualitative and quantitative information in the as-built BIM model.	23.As-built model 24.Construction acceptance
Facility management	Model for facility management	Adding qualitative and quantitative model information for facility management.	25.Facility management model

2.3. Cost of BIM Use Services

As addressed in Introduction, there not many works reported on the cost of BIM use services due to the diversity of project characteristics and the different levels of BIM implementation in project. According to the survey of Becerik-Gerber and Rice [9], 59% practitioners of BIM considered no extra space requirement, while 41% believed no extra labors required, 21% believed labor requirement decreases and 13% believed more labors are required to implement BIM.

A wide survey to more than 2,000 industrial BIM practitioners by McGraw Hill Construction [27] showed that most respondents believe that the BIM implementation cost is less than 0.5% of total net revenue of the firm; where 39% respondents consider hardware cost increases by 0.5~1.49%, while 34% believed software cost increases the most.

Olatunji [28] found that 55% of BIM implementation cost is attributed to software, while 22% attributed to hardware cost and 18.2% attributed to training cost.

According to the statistics of the Construction and Planning Agency (CPA), Ministry of Interior, Taiwan in performing 9 public construction projects, the BIM implementation cost was ranging from 0.09~0.43%, and the average cost is 0.19% of overall construction cost.

A more definite reference for the BIM implementation cost suggested by the Public Construction Commission (PCC) of Taiwan was 0.4~0.5% of overall construction cost both for design and construction phases. Such a reference is similar to that suggested by 'Taiwan BIM Guide' [14], which is 1% of overall construction cost for the whole construction project lifecycle including facility operation and maintenance phase. In this paper, the 1% overall BIM implementation cost is also considered as a standard reference for all 25 BIM uses defined by 'Taiwan BIM Guide'.

3. Research Methodology

The research aims at allocating the BIM cost required for the 25 BIM uses of 'Taiwan BIM Guide' defined by the ABRI shown in Table 1. An Analytic Hierarchy Process (AHP) method is employed to determine the relative requirements of costs for the 25 different BIM uses by surveying the BIM practitioners from the 10 selected public social housing projects owned by the Taoyuan City Government. Basic information of the 10 selected public social housing projects is shown in Table 2.

Table 2. Basic information of the 10 selected public social housing projects.

No.	Project ID	Building Description	Floor (m^2)	Construction budget (NT$)	BIM cost (NT$)
1	CL-1	Twin towers: 14-F+Sub-3F.	21,104	754,112,852	3,914,734
2	CL-2	Triple towers: A-17F, B-16F, C5F+Sub-3F.	33,917	1,118,310,000	3,267,567
3	CL-3	Triple towers: 20-F+Sub-3F.	49,233	1,710,879,886	8,886,179
4	CL-4	Triple towers: 20-F+Sub-3F.	49,309	1,736,701,047	9,031,131
5	BD-1	Triple towers: 18-F+Sub-3F.	52,807	1,603,520,000	4,682,491
6	BD-2	Twin towers: 19-F+Sub-3F.	35,623	1,092,876,556	3,000,000
7	BD-3	Four towers: 21~22-F+ Sub-2F.	75,696	2,441,000,000	12,440,000
8	LJ-1	Triple towers: 11-F+Sub-3F.	14,231	514,765,288	2,619,246
9	LJ-2	Four towers: 14-F+ Sub-2F.	49,372	1,472,820,731	3,796,387
10	JL-1	11 towers: 11~13-F+ Sub-2F.	138,608	4,838,626,974	24,462,651

An AHP questionnaire is designed to compare the relative importance on cost requirements among the 25 BIM uses based on the hierarchy of Taiwan BIM Guide, i.e., 6 phases · 25 BIM uses as shown in Fig. 1. The questionnaire was prepared and provided to the project owner, the Office of Housing Development of Taoyuan City Government.

In order to make sure all BIM practitioners of the projects fully understand the definition of the 25 BIM uses and the process of relative preference comparisons of BIM, presentations were held to those practitioners by the research team. Then the project owner helped distribute the questionnaire to all participants of the 10 public social housing projects and collect the responses. The responses were collected twice: first collection was at the end of 2017 with 26 responses. It was figured out that most of the responses were from the designers or engineering consultants, since the projects were in their early stages. As a result, the second survey were conducted and collected in May of 2018. Finally, 50 valid responses were collected and analysed.

Due to the business schedule of the project participants, the iterative surveys of the traditional AHP were not possible. As a result, the Adaptive AHP Approach (A^3) [25,26] was adopted to analyse the 50 valid responses from the surveys. In performing A^3 processing, the CR was relaxed step wisely from 0.1 to 0.2, to 0.3, in order to obtain sufficient samples (default No. of sufficient samples was set to be 33 to meet the requirement of Central Limit Theory of Statistics). After analysing the 50 valid questionnaire responses, relative weightings in each level of the hierarchy of Fig. 1 were calculated to yield the final criterion weightings for all 25 BIM uses.

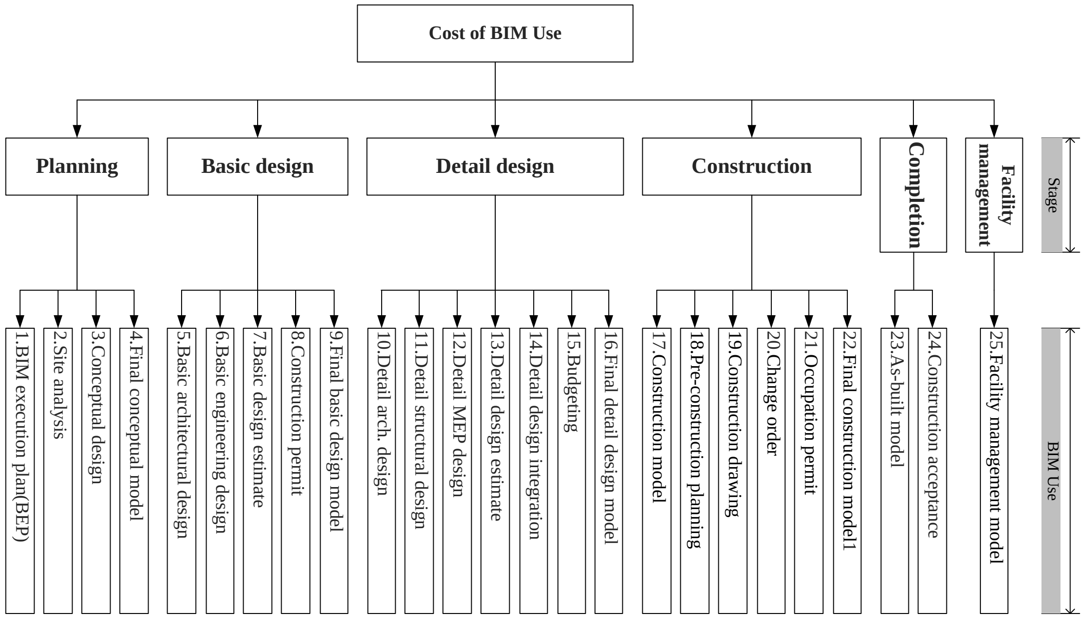

Fig. 1. Hierarchy of the 25 BIM uses of Taiwan BIM Guide.

4. Result Analysis

The analysis results of AHP via A^3 process are presented in this section.

4.1. Profile of participants

The profile information of the respondents of the two AHP questionnaire surveys help in Dec. of 2017 (1^{st} survey) and May of 2018 (2^{nd} survey) are shown in Table 3. It is noted that the No. of the General and DB contractors were increased in the 2nd survey due to the project execution phase. Other profile information of the respondents is shown in Fig. 2.

Table 3. Profile information of the 50 respondents.

Project participants	No. of respondents		
	1^{st} survey	2^{nd} survey	Sum
Owner/CM	5	7	12
Consultant	10	2	12
Architect	7	1	8
Contractor/DB	4	14	18
Total respondents	26	24	50

4.2. Results of A^3 processing

After AHP questionnaire survey, 7 pairwise weighting matrixes PWMs) are obtained from each respondent: (1) Phases—6 criteria; (2) Planning—4 criteria; (3) Basic design—5 criteria; (4) Detail design—7 criteria; (5) Construction—6 criteria; (6) Completion—2 criteria; and (7) Facility management—1 criterion. As the No. of criteria is < 3 in AHP, there is no inconsistence (CR=0) for the PWMs; thus, there is no need to reprocess the PWMs of (6) and (7). However, A^3 reprocessing is required for the rest 5 PWMs when the CR of the PWM is · 0.1 [26]. The No. of acceptable returns (CR<0.1) in the original questionnaire responses for the 7 PWMs are: (1) Phases—12; (2)

Planning—15; (3) Basic design—17; (4) Detail design—16; and (5) Construction—14. Using the stepwise relaxation of CR in the A^3 process, all PWMs of the AHP meet the requirement of 33 acceptable responses with adapted CR < 0.1. The No. of acceptable responses for each PWM is follows: (1) Phases—35; (2) Planning—36; (3) Basic design—41; (4) Detail design—33; and (5) Construction—37. As a result, the relaxation of CR stops at CR = 0.3. An example of A^3 adaptation for a PWM is shown in Table, where DI is defined in Eq. (1). In Table 4, the adaptation stops at Generation 3 as CR has decreased to 0.989 < 0.1.

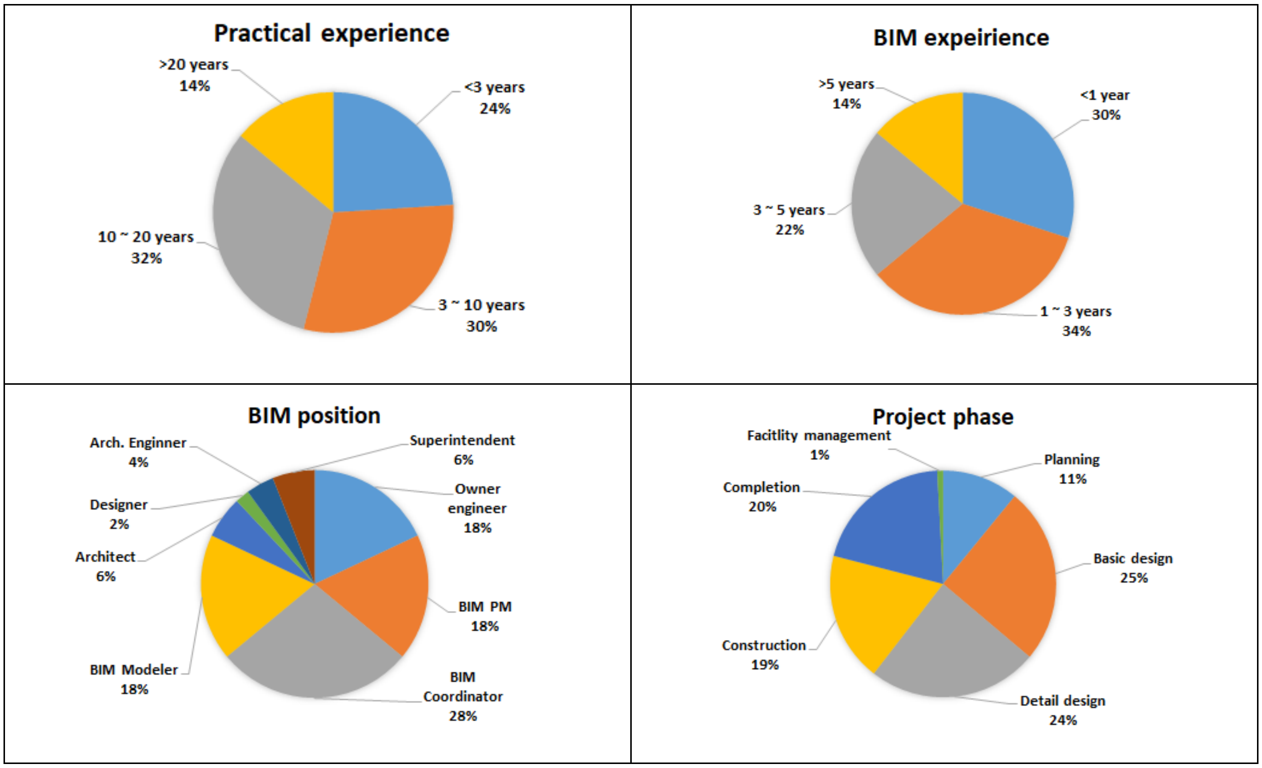

Fig. 2. Profile information of the 50 respondents.

Table 4. Example of A^3 adaptation

No. of generation	CR	λ_{max}	Difference Index (DI)
-	0.2040	4.5507	1.0000
1	0.1759	4.4749	1.0047
2	0.1653	4.4464	1.0050
3	0.0989	4.2670	1.0481

$$DI = \frac{\left|G./G^*\right| + \left|G^*./G\right|}{n^2 - n} \quad (1)$$

Where 'G' is the value of an element in the PWM before adaptation; 'G' is the value of an element in the PWM after adaptation; 'n' is the number of criteria in the PWM; './' is the element-wise division operator.*

4.3. Relative weightings of cost requirements for the 25 BIM uses

The resulted cost requirement weightings for the 25 BIM uses after A^3 adaptation are shown in Fig. 3 as grouped by phases.

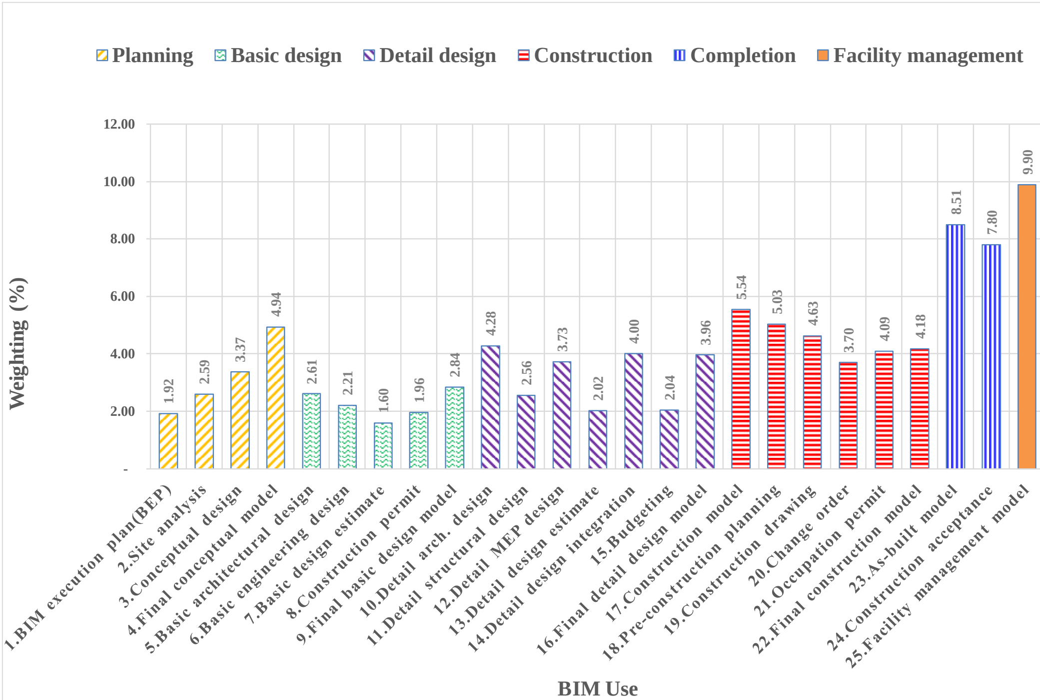

Fig. 3. Relative weightings of cost requirements for the 25 BIM uses (grouped by phases).

The cost requirement weightings for the 25 BIM uses in decreasing order are shown in Fig. 4. It is noted that the most significant cost demanding BIM use has been '25-Facility management.

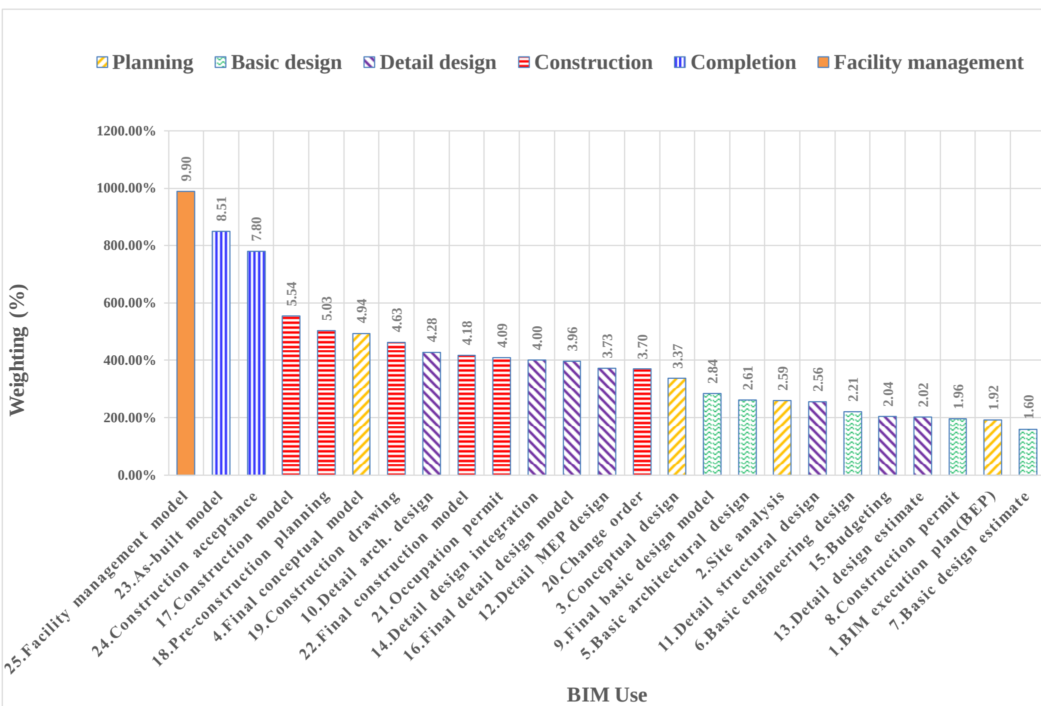

Fig. 4. Relative weightings of cost requirements for the 25 BIM uses in decreasing order.

5. Application Demonstration

In this section, how the obtained relative cost requirement weightings for the 25 BIM uses can be employed to plan a BIM project is demonstrated. The selected case project is a high-rise residential construction project. Total floor area of the project is 34,860 m^2, with construction budget of USD$37.77 million. Assuming that the BIM service cost is 1% of the construction budget, the allocated required costs for all 25 BIM uses are shown in Table 5.

Table 5. BIM cost allocation for six phases.

Phase	Weightings (%)	Cost (USD$)	BIM service provider
Planning	12.83%	48,453	Owner/Consultant
Basic design	11.21%	42,335	Architect
Detail design	22.59%	85,311	Architect/DB
Construction	27.17%	102,608	GC/DB
Completion	16.30%	61,557	GC/DB
Facility management	9.90%	37,387	FM firm

Table 5 demonstrates an example of planning BIM service cost for different project phases (by different BIM service providers). When different project delivery models were used for the same project, the BIM service budget should be planned differently: (1) for D/B/B project delivery model—the Architect (Designer) should be provided with USD$127,646 for basic and detail designs and the general contractor (GC) should be provided with USD$164,165 for construction and completion BIM works; (2) for Design/Build (D/B) model—the D/B contractor (including design and contractor) should be provided with USD$249,476 for detail design, construction and completion BIM works, while the planning consultant should be provided with USD$ 90,788 for planning and basic design BIM works.

6. Discussion

An interesting observation was found while analysing the different relative weightings in AHP questionnaire surveys. As shown in Table 6, the relative weightings by different project participants depicts some profound implications in BIM practice discussed in the following:

- The Owner emphasizes more on Completion and FM phases, while less on BIM uses in Planning phase;
- The Architect considers that Basic design deserves more BIM budget and less on BIM uses in FM phase, which is completely opposite to the Owner's opinion;
- Interestingly that the engineering consultant emphases more on BIM uses in Construction phase as he/she need to supervise that, while also give less concerns on FM BIM use that is similar to the Architect.;
- On the contrast to the Owner, the Contractor/DB emphasizes more on Planning phase, although it is irrelevant to Contractor/DB's responsibility. He/she gives less concerns to Detail design, which may be due to that the Contractor usually rebuilds the BIM model in practice.

Table 6. Relative weightings by different project participants

Party	Planning	Basic design	Detail design	Construction	Completion	FM
All	12.83%	11.21%	22.59%	27.17%	16.30%	9.90%
GC/DB	16.16%	11.30%	20.88%	25.25%	15.98%	10.47%
Owner (CM)	4.24%	9.91%	24.30%	26.74%	21.60%	13.21%
Architect	11.66%	13.63%	24.31%	26.54%	16.23%	7.61%
Consultant	14.50%	9.94%	24.26%	33.51%	11.74%	6.06%

7. Conclusion and Recommendation

This paper presents a case study on the estimating and allocating the costs required for BIM services based on the 25 BIM Uses defined by the 'Taiwan BIM Guide' developed by the Architecture and Building Research Institute (ABRI), Ministry of the Interior (MOI), Taiwan, for implementation of BIM by local construction industry. To estimate and allocate required costs for various BIM uses, the current study proposes a method integrating traditional AHP and A^3 approaches to determine the relative requirements of costs for different BIM uses by surveying the BIM practitioners from the 10 public social housing projects owned by the Taoyuan City Government using an Analytic Hierarchy Process (AHP) method. A BIM use cost allocation guideline is provided as a reference to the BIM practitioners to determine the required costs for different BIM Uses. Finally, the relative weightings of cost requirements for the 25 BIM uses are identified. Such a method to determine the relative BIM service cost requirements were not found in any literature. The results can be applied to plan the BIM service costs for different project delivery models of a building construction project. Demonstrated case studies are also presented to show the feasibility of their applications.

Although a method for BIM service cost allocation has been developed, the exact BIM cost requirements for different project types have not yet been defined. In the demonstrated case, 1% of total construction budget was assumed for BIM service cost. This is also suggested by the ABRI and PCC of Taiwan government. However, different BIM guides will result in different BIM service cost requirements. It implies more research efforts should be spent in this topic.

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Analyzing BIM interoperability for LCA purposes

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Abstract

The use of building information modelling (BIM) is increasingly popular and results in the BIM model becoming the central data source in a construction project. The information available in BIM is hard to use because it lacks interoperability. This paper assesses every strategy to share data from BIM in order to support a life cycle assessment (LCA) for a whole building at every step of the BIM model design. Every open file format concerning the BIM is analyzed to determine if one file format can fulfill the data requirements of an LCA. Among all of these file formats, IFC is the best-known and most detailed format. An in-depth analysis of the IFC data schema and syntax is performed to determine whether the construction industry requires a specific file format for LCA purposes or whether one of the existing open file formats can be used as a data source.

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Keywords: BIM; Interoperability; LCA; Open format file

1. Introduction

In recent years, a wave of new technology has emerged in the construction industry, including building information modelling (BIM) technologies. With these, a lot of new information is readily available for analysis and enables the optimization of building design. This new information can also be used to coordinate the construction process, to optimize cost and for many more aspects. One of these aspects is sustainability. Today, given that the construction industry contributes more than 39% of greenhouse gas emissions in the US [8,10], stakeholders of a building project are concerned with their environmental footprint [2,7,10]. One of the common processes used to assess the environmental impact of a product is to perform a lifecycle assessment (LCA). The process is well known but underused [7] in the construction industry. This paper will assess how to use new information from BIM in the design process of a building to perform an LCA for a whole building at each step of the building project.

2. Literature review

2.1. LCA of a whole building

Determining the LCA of an entire building is a complex process that needs a lot of data [3,5,7,10,11]. To simplify the LCA process, many research projects use the BIM model as their data source [3,5,8,10] but it is not as simple as it

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seems and the lack of interoperability of BIM software is well documented [2,4,8]. Sabol [9] proposes three strategies to improve the interoperability of the BIM data: 1) designing software that uses an application program interface (API); 2) using an open database connectivity (ODBC) technology; or 3) using a specialized file format.

Using an API allows us to create new features on top of BIM software. The new feature can be as simple as the ability to export BIM data in a new file format or as complex as a complete LCA software. Using an API is the most flexible strategy of the three proposed but requires a high level of knowledge in software engineering and will require adjustments whenever the BIM software version changes.

The second recommended strategy is to use ODBC technology. This technology can extract the data from a BIM model and store it in a database like Microsoft SQL Server. Once the data is transferred into a database, it is easy to query and extract the desired data by using the Structured Query Language (SQL). The downside of ODBC technology is that the resulting data schema is not standardized and would be different for each BIM software currently on the market.

The third strategy is to use a specialized file format. For this strategy, only non-proprietary formats would be considered because proprietary formats, like the Revit file format, are regulated by license agreements that prohibit their use in other software without prior agreement. Today, many open file formats exist for the construction industry such as: BIMXML, CityGML, COBie, gbXML and IFC. After an in-depth analysis of each of these formats, it was concluded that none contained the required data for an LCA, with the exception of the IFC file format (see Table 1).

Table 1. Focus of open formats available

Format	Focus	Building perspective described as
BIMXML	Simplified spatial building model	Spaces and rooms
CityGML	Model a city	Massing forms
COBie	Information handover for facility management	Component, object’s type, assembly, space
gbXML	Operational energy analysis	Space and room with thermal property
IFC	Building modelling	Object with a high level of detail

The list of data elements required for an LCA at each step of the BIM model design is described by Dupuis [3] (see Table 2), and only the IFC file format possesses enough detail to describe each layer of material of an assembly and provide quantities (area and volume) by object.

Table 2. Data needed for each level of development (LOD) of a BIM model for LCA purposes

LOD	Definition	Data needed for LCA
100	The element is represented with a generic representation	Metadata about the building Massing form quantities
200	The element is represented with a generic object	Objects / Object’s type Uniformat II code Objects / Object’s type quantities
300	The element is represented as a specific object without a specific assembly or with partial assembly	Objects / Object’s type quantities Material quantities Material function (to detect missing layer)
350	The element is represented as a specific object with a specific assembly	Material quantities Objects / Object’s type quantities
400	The element is represented as a specific object with a specific assembly and with the installation detail	Material quantities Objects / Object’s type quantities
500	The element is a field verified representation	Material quantities Objects / Object’s type quantities

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3. Analyzing IFC for LCA purposes

The IFC file format is the best-known open file format in the construction industry and has the greatest potential for standardizing a BIM data exchange [9]. Today, almost every BIM tool supports the export or the import of IFC files and the format is somewhat standardized. The syntax of IFC, called STEP, is described by the international standard ISO 10303 and its data schema defines more than a thousand entities, all described by the international standard ISO 16739-1 [6]. Based on these two standards and some IFC files exported from different BIM tools, we assessed whether the IFC file format is suitable as a data source for LCA purposes. As described in Table 2, to be a suitable data source, the IFC file must contain the following information:

- Quantities related to:
    - Massing form;
    - Object;
    - Object's type;
    - Material.
- Informations required to impute or qualify quantities:
    - Material's function;
    - Uniformat II code for both Object and Object type;
    - Metadata about the building.

The following sections describe these data items in more detail.

3.1. Quantities

The quantity of an object's type can be calculated by aggregating the quantity of every object associated with this object's type. The quantity of a massing form, given that it is an object type, is calculated in the same way as any other object's type. Lastly, the quantity for each material is the product of the object type quantity multiplied by the ratio of this material for that object type. The determination of the ratio is explained later in this section.

To extract the quantity of an object from the IFC file format, two methods are possible. The first method is to calculate the area and the volume of each object directly from 3D geometry. The IFC file format describes 3D geometry using a combination of one or multiple entities based on 24 types of representations [1]. Due to the scope of our research project, extracting the area and volume in 24 different ways was too long and too complex.

The second method is to extract the quantity based on the parameters of the object. With this method, the first challenge is that the user needs to set all the proper options in the IFC file export window so as to export the IFC file with the required data for the LCA of a whole building. In our tests, we found that the contents of two IFC files differed for different BIM software, even if all the IFC file export options are properly set. As an example, we compared two IFC files generated by two different versions of Autodesk Revit, where the object's quantity is linked to an object by a different property set with different parameter names (see Table 3). This variation could be managed by mapping property names and property set type to each BIM tool and BIM tool version.

Table 3. Differences between two IFC exports

Element	File 1 (See Appendix A)	File 2 (See Appendix B)
Software	Autodesk Revit 2017 (ENU)	Autodesk Revit Architecture 2011
Property set type	IFCELEMENTQUANTITY	IFCPROPERTYSET
Property set name	BaseQuantities	PSet_Revit_Dimensions
Area property name	GrossSideArea	Area
Volume property name	GrossVolume	Volume

The next piece of information to extract from the IFC file is the ratio of each material in the object and its function. In our observations, most of the time the assembly is described in the object's type. The object is linked to the object's type by the entity "IFCRELDEFINESBYTYPE" and the list of material is linked by the entity "IFCRELASSOCIATESMATERIAL". The ratio of each material in the object is expressed with a thickness by square meter in the entity "IFCMATERIALLAYER". The volume of material can be calculated by multiplying the area of the object by the thickness of the material layer.

3.2. Information required to impute or qualify quantities

The detection of a missing layer of an object's type is based on the material function (e.g. an exterior wall missing a layer of material with the function "Thermal/Air layer"). However, the material's function is not found in any analysed file. After further analysis of the IFC data schema, the IFC format cannot contain the description of the function of a material or any additional information.

The last element needed concerning the object or the object's type is the Uniformat II code. The Uniformat II code helps to identify more precisely an object or an object's type when its description is irrelevant (e.g. "Product A" to describe an exterior wall). Uniformat II code is associated with the object or the object's type with the entity "IFCRELASSOCIATESCLASSIFICATION".

The metadata helps to impute quantity more precisely or to share information that affect the whole building. A metadata is a parameter that is structured with a name and a value (e.g. Name: "Building a lifetime", Value: "75"). After several tests to register global parameters in Autodesk Revit and export IFC files, we found that the metadata parameter was not transferred to the IFC file in any way. After validating the data schema of IFC, we found that IFC contains a global entity named "IFCBUILDING" representing the building. To add information that applies to the whole building, such as metadata, an entity "IFCPROPERTYSET" needs to link to the entity "IFCBUILDING".

4. Conclusion

The construction industry has various files that can share specialized information but at the time of writing this paper, no file format is specialized to share information between BIM and an LCA. After comprehensive analysis, it was determined that the IFC was the best file format to be used as a data source for the LCA of a whole building. Almost all of the information needed for an LCA can be contained in the IFC file. Our analysis has shown that the contents of an IFC file varies greatly based on the BIM software used and the export options selected by the user. All of these variations need to be considered to use the IFC file format and with more than a thousand entities to examine and understand, it is a complex and tedious task. For global parameters, we have seen that IFC can handle this kind of information but Autodesk Revit does not use IFC to its full potential. The only drawback with the IFC data schema is its inability to add information for a material, such as the material's function. This information is crucial for detecting missing layers in an assembly. The IFC format will continue to evolve, becoming more flexible and maybe one day, BIM software will use more of the IFC features to support more information with regards to material. Meanwhile, the industry will need to create a new specialized format to share data between BIM and the LCA. This new specialized file format will need to be generated with an API of a BIM software until it becomes fully supported by the BIM software itself or until a new version of the IFC format can fulfill all the data requirements of the LCA.

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Appendix A. IFC file 1

File generated from the Revit 2017 example file "Sample System Project"

```
#1= IFCORGANIZATION($,'Autodesk Revit 2017 (ENU)',$,$,$);
#5= IFCAPPLICATION(#1,'2017','Autodesk Revit 2017 (ENU)','Revit');
…
#537293=IFCWALLSTANDARDCASE('3XrBtx9eX7mQE6EqWHPk2W',#41,
        'Basic Wall:STB 30.0 Rot:573298',$,'Basic Wall:STB 30.0 Rot:563456',#537266,#537291,'573298');
#537304= IFCRELDEFINESBYPROPERTIES('1RmJMst4LCfPj0I4gbOuNN',#41,$,$,(#537293),#537302);
#537302= IFCELEMENTQUANTITY('2RnzV9aiTCPvHT7sUlrItz',#41,'BaseQuantities',$,$,
        (#537296,#537297,#537298,#537299,#537300,#537301));
#537296= IFCQUANTITYLENGTH('Height',$,$,3405.82826312155);
#537297= IFCQUANTITYLENGTH('Length',$,$,8235.00000008147);
#537298= IFCQUANTITYLENGTH('Width',$,$,300.);
#537299= IFCQUANTITYAREA('GrossFootprintArea',$,$,2.47050000002445);
#537300= IFCQUANTITYAREA('GrossSideArea',$,$,28.0469957470834);
#537301= IFCQUANTITYVOLUME('GrossVolume',$,$,8.41409872412505);
…
#537324=IFCWALLTYPE('3XrBtx9eX7mQE6EqWHPiRI',#41,
        'Basic Wall:STB 30.0 Rot',$,$,$,$,'563456',$,.STANDARD.);
#1046230= IFCRELDEFINESBYTYPE('2P_uP6Oz13fO3cLNLBR5qm',#41,$,$,(#537293,#537513),#537324);
#537331= IFCRELDEFINESBYPROPERTIES('3gAvc6bvjA3Ae2Rv7kN7H3',#41,$,$,(#537293),#537329);
#537329=IFCPROPERTYSET('3XrBtx9eX7mQE6CBKHPk2W',#41,'Pset_WallCommon',$,
        (#537325,#537326,#537327,#537328));
…
#1041241= IFCRELASSOCIATESMATERIAL('0g2kHgMgLAzPXey59ofISJ',#41,$,$,(#537324),#537320);
#537320= IFCMATERIALLAYERSET((#537318),'Basic Wall:STB 30.0 Rot');
#537318= IFCMATERIALLAYER(#537308,300.,$);
#537308= IFCMATERIAL('Stahlbeton - Ortbeton - Rot');
```

Appendix B. IFC file 2

File from NIBS website: https://portal.nibs.org/files/wl/?id=4DsTgHFQAcOXzFetxbpRCECPbbfUqpgo

```
#1=IFCORGANIZATION($,'Autodesk Revit Architecture 2011',$,$,$);
#2=IFCAPPLICATION(#1,'2011','Autodesk Revit Architecture 2011','Revit');
…
#3797=IFCWALLSTANDARDCASE('2O2Fr$t4X7Zf8NOew3FNtn',#33,
    'Basic Wall:Exterior - Brick on Block:138062',$,
    'Basic Wall:Exterior - Brick onBlock:130892',#3781,#3796,'138062');
```

#3871=IFCRELDEFINESBYPROPERTIES('35P9FVrsf6NgTkU$WnQOmz',#33,$,$,(#3797),#3870);
#3870=IFCPROPERTYSET('30Iq7jVDv0KRtnFHa6i3mq',#33,'PSet_Revit_Dimensions',$,(#3822,#3823,#3824));
#3822=IFCPROPERTYSINGLEVALUE('Length',$,IFCLENGTHMEASURE(8.383000000000001),$);
#3823=IFCPROPERTYSINGLEVALUE('Area',$,IFCAREAMEASURE(13.61184000000174),$);
#3824=IFCPROPERTYSINGLEVALUE('Volume',$,IFCVOLUMEMEASURE(5.676137280000731),$);

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Application of Building Information Modeling in Facility Management: A Case Study of a Commercial Project

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Abstract

Adoption of Building Information Modeling (BIM) in Facility Management (FM) is effective for integrating Architecture, Engineering, and Construction (AEC) for providing better services to the end-users of a project for a whole lifecycle. Real estate sector in India has witnessed high growth in recent times with the rise in demand for commercial as well as residential spaces. Most of them are facing issues related to AEC and are not been able to manage such on-site problems resulting in delaying of projects. It is better to develop proper coordination to provide integrated information about AEC in advance to reduce conflicts occurring during the construction and operational phase. The operational phase of a building is the main contributor to the building lifecycle cost and estimates show that the lifecycle cost is five to seven times higher than the initial investment costs and three times the construction cost. There is a lack of real-life case studies on BIM in FM especially for existing assets even though new constructions representing only 1-2 percent of the total building stock in a typical year. So a case study of a commercial project is taken for Facility Management using BIM as a tool and analyzed for probable solutions for mitigating AEC conflicts. The findings from the study demonstrate that BIM value in FM stems from improvement to current manual processes of information handover; improvement to the accuracy of FM data, to the accessibility of FM data and in work order execution ultimately improving the sustainability of building construction projects.

Peer-review under responsibility of the scientific committee of the Creative Construction Conference 2019.

Keywords: Building Information Modeling (BIM); Facility Management (FM); Architecture, Engineering, and Construction (AEC); Building Construction; Sustainable Development

1. Introduction

Building Information Modeling (BIM) is an intelligent 3D model-based process that gives architecture, engineering and construction (AEC) professionals the insight and tools to more efficiently plan, design, construct and manage buildings and infrastructure. BIM is a process of creating and managing 3D building data during its development and works as three-dimensional, real-time, dynamic building modeling computer program in which you can increase productivity throughout building design and construction. [1] Facilities management (FM) is an umbrella term under which a wide range of property and user-related functions are brought together for the benefit of the organization and

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its employees as a whole [2] also it is holistic in nature, covering everything from real estate and financial management to maintenance and cleaning. [3]

Building lifecycle cost depends mainly upon the operational phase of the building. Estimates show that the lifecycle cost is five to seven times higher than the initial investment costs and three times the construction cost. [2, 4] BIM as a tool enables efficient management of facilities which leads towards improved lifecycle cost of a project. Due to the inefficiencies in the building construction industry, several governments around the world mandate the use of BIM for improving productivity. For example, the UK Government has mandated BIM level 2 − federated models held in separate discipline "BIM" tools with attached data − on all centrally procured projects from 2016, including the handover of digital data required for the operational phase. [2]

In this paper, the applications of BIM in FM for building construction industry are explored for implementing in planning, designing, construction, and operational processes. In investigating BIM applications in FM have mainly focused on new buildings, even though new works making up only 1-2 percent of the total building stock in a typical year [5] and yet not been raised in today's construction industry. There is also a lack of real-world cases on BIM applications in FM. [6] So, the applicability of BIM in FM for is being identified through a real-world case study of a commercial project named Eden Ceramic City situated at Morbi, Gujarat, India.

2. Literature Review

2.1. The scenario of Building Information Modeling for Facility Management in developing countries

Building Information Modelling (BIM) is widely seen as a catalyst for innovation and productivity in the construction industry. Over the last few years, there has been an ascending push for Building Information Modeling across the built environment sector because BIM is changing the construction and infrastructure industries. The information collected through a BIM process and stored in a BIM-compliant database could be beneficial for a variety of FM practices, such as commissioning and closeout, quality control and assurance, energy management, maintenance and repair, and space management. [6] However, the potential of BIM technology to facilitate design-construction collaboration and to reduce the construction coordination costs, schedule and request for information (RFI)s has not yet been achieved. [7]

Building information modeling (BIM) in facilities management (FM) applications is an emerging area of research based on the theoretical proposition that BIM information, generated and captured during the lifecycle of a facility, can improve its management. BIM value in FM stems from improvement to current manual processes of information handover; improvement to the accuracy of FM data, improvement to the accessibility of FM data and efficiency increase in work order execution. [2]

In developing countries majorly, the building construction industry is dealing with a low-income group (LIG) and a medium income group (MIG) where BIM can assist a more sustainable construction process that in turn may contribute to exterminating poverty in developing countries. [8] Research has established how construction firms struggle from several limitations having to do with the socio-economic and technological environment found in developing countries. Examples of issues preventing BIM adoption include a shortage of IT-literate personnel as well as an absence of national BIM implementation programs. Findings include that construction firms of developing countries rely on outsourcing of IT services or developing tweaks or workarounds, like using fake IT licenses, for saving cost and enabling BIM. [9]

2.2. Applicability of Building Information Modeling in Facility Management

The FM industry is quite rigid in its approach to new technology, and unless benefits of BIM in FM is clearly proven, its acceptance in the FM industry will continue to be low. [6] Indeed, there is a lack of demand from clients for BIM [10], which is exacerbated by a general lack of collaboration between project stakeholders for modeling and model utilization. [6] The lack of awareness by clients is exacerbated by a shortage of BIM skills and understanding by FM professionals [4] and therefore, these two factors together are creating a challenge for BIM adoption in FM applications. The lack of processes for updating the designed model with as-built information is considered among the top challenges for BIM in FM applications [11] where roles and responsibilities for providing the data and maintaining the model are not well defined. [6]

Facility managers have traditionally been included in the building lifecycle in a very limited way and at the late phase of facility handover to clients. [12] Additionally, design decisions are not usually challenged for their impact on operational cost or maintenance. [13] Current facility maintenance contractors are paid to survey the existing building to capture as-built conditions and the owner will have to pay over and over – once for the construction contractor to complete the documents at the end of construction – and again for the maintenance contractor survey and the start of every contract. [14] As a result of these challenges, BIM data for FM is either lacking or inadequate. “The FM field relies heavily on getting usable data from a BIM to do anything meaningful with it. All too often, this data is not really there or is inaccurate, as the model has not been updated with any design changes made after the design phase and is therefore not an accurate model of the facility as it is built”. [15] Because of the duplication of information there is a need for improvement in handover data and maintenance of that data throughout its lifecycle.

Current information transformation system is manual which is based on the paper documents containing lists of equipment, product data, warranties, spare parts, maintenance schedules, etc. and essential to support the management of the facilities by the owner and facilities managers. In this system information handed over is often incomplete and inaccurate. [16] The industry is spending lots of resources in terms of money and manpower in recreating such information and working with inefficient workflows. [17]

However, using BIM in FM can improve the current information handover processes [18] because BIM data and information collected during the building lifecycle will reduce the cost and time required to collect and build FM systems. [19] For example, data regarding spaces, systems, finishes, etc., can be captured in digital format within a BIM and do not require to be re-created in downstream FM systems. [20] The ability to capture manufacturers information within 3D parametric objects reduces the need for duplicating asset information. [21] BIM is considered as an enabler of improved data quality and reliability which will, in turn, result in increased workforce efficiencies. [19]

The ability to extract and analyzing views from BIM, specific to various needs and users, will provide information to make decisions and improve the delivery of facilities. [12] For example, 3D visualization can help FM technicians to better utilize their cognitive and perceptual reasoning for problem-solving. [22] BIM visualization provides accurate geometrical data that has never been possible before and can support the analysis of building proposals and the simulation and benchmark of performance. [3] For example, intelligent algorithms could be created to automate decision making for FM applications that have never been possible before the addition of digital data. [23]

Another important BIM in FM applications outlined literature is in space management, emergency management, energy control, and monitoring and personnel training and development ([24] [25] [19] [26] [22]). There are also suggestions that adopting BIM in FM will facilitate the future involvement of facility managers at a much earlier design stage, in order to convey their input and influence on the design and construction of a building. [12] The adoption of BIM in FM is also expected to provide ways for managing knowledge about building operation which can be utilized in future designs. [4]

3. Methodology

This paper aims to identify the application of BIM in FM for a commercial project. A likely application of BIM in FM has been explored in the literature review. However, there is also a need to test this value and also explore further how BIM can add value in FM of existing assets. A case study was conducted to investigate the value of BIM in managing utilities, spaces selected as a specific FM function. Also through a questionnaire and interviews with AEC professionals derived applications is being verified. The flow of methodology is shown in Fig. 1.

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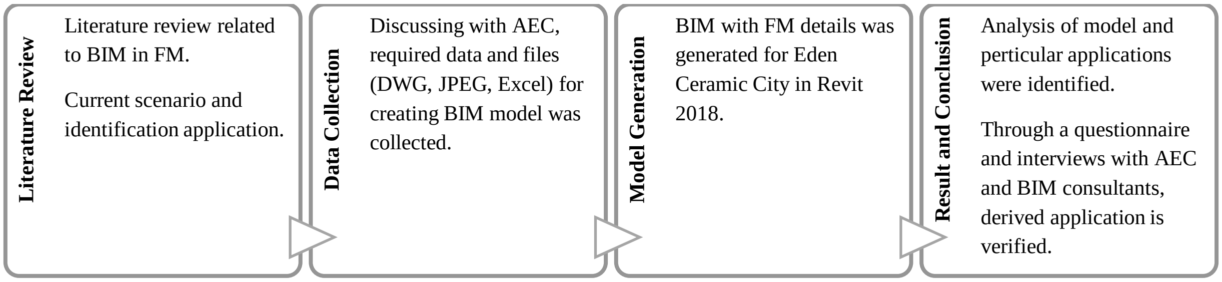

Fig. 1. Flow of Methodology

4. Case Study

The case study was conducted on a commercial project named Eden Ceramic City situated in Morbi, Gujarat, India. This project is made up of 48 Corporate Display Centres (CDCs) and 12 Corporate Houses (CHs) with a built-up area of about 50,000 m^2 (Fig. 2). For creating a BIM model, existing floor plans in DWG format, scans of the original elevations, sections in JPEG format, and utility information in Excel databases are used. As the case study involves an existing asset, there are key challenges that the application of BIM for FM purposes has to consider. Discussing with AEC involved in this project the strategic issues and the business case for migrating from the current FM processes to BIM-based FM processes in managing the existing utilities of a project is identified. The developer was interested in updating drawings and details for this project to prepare an effective operation and maintenance strategy for a lifecycle of a building. In the traditional technique, this process requires a manual update which leads towards duplication of work and the efficiency of work is not been achieved yet.

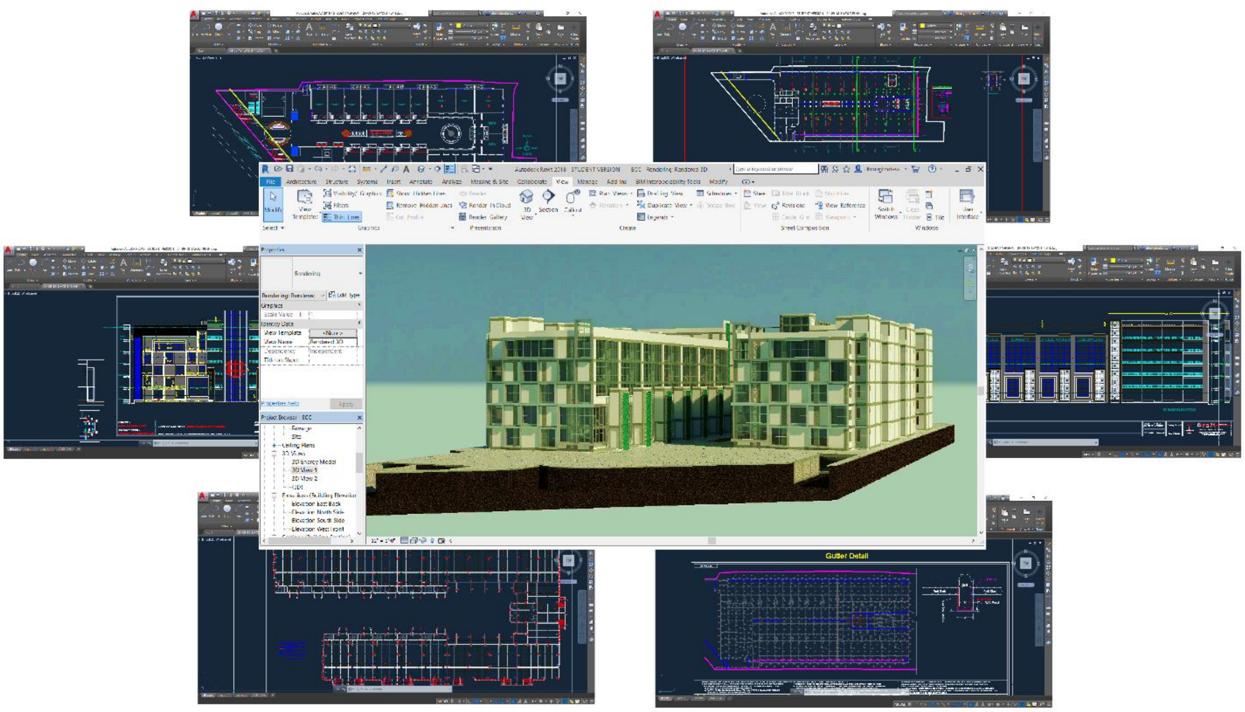

Fig. 2. From traditional drawings to integrated BIM of Eden Ceramic City

5. Results and Outcomes

The outcomes from the case study demonstrated with practical examples of how BIM can add benefits in planning, designing, operation and maintenance and management of information. Discussion with AEC professionals conducted during the case study revealed a further challenge which is inherent in the significant differences of lifespans in BIM technologies, FM technologies, and buildings. FM organizations have to take care of working with different information and data standards in the mid and long terms instead of adapting their business processes to fit a specific technology. The applications explored are currently theoretical and will be used by the AEC in order to implement an integrated BIM strategy in the following ways:

5.1. Effectiveness in working with Building Information Modeling

The efficiency of processes associated with managing spaces, and utilities such as updating geometric and non-geometric information, came immediately while the functionalities of BIM for FM were explored in the project. Using BIM in FM, the creation of geometric information and the inclusion of specific FM information allows automatic updating of required schedules; producing instant sections, elevations, three-dimensional visuals and renders, and generating drawing sheets from a single integrated model shown in Fig. 3. Additional information relating to essential maintenance, emergency equipment, escape routes, accessibility, etc. can be easily traced, updated and reported in schedules. Moreover, the AEC identified that BIM in FM can enlarge the available BIM functionalities which enhance FM services such as root finding, fault reporting, development, and refurbishment option generation, and assessment of building performance ultimately leads towards a reduction in response times, with detailed knowledge assigned to specific buildings, levels, rooms, etc. The developed BIM for FM was used to trial option appraisal for redevelopment and refurbishment as floor plans, sections, elevations, and 3D rendered views that could be quickly displayed and assessed in Fig. 3. Such functionalities provide time and costs efficiency as a future FM alternative and represent a platform for more accurate strategic decision making from a management perspective.

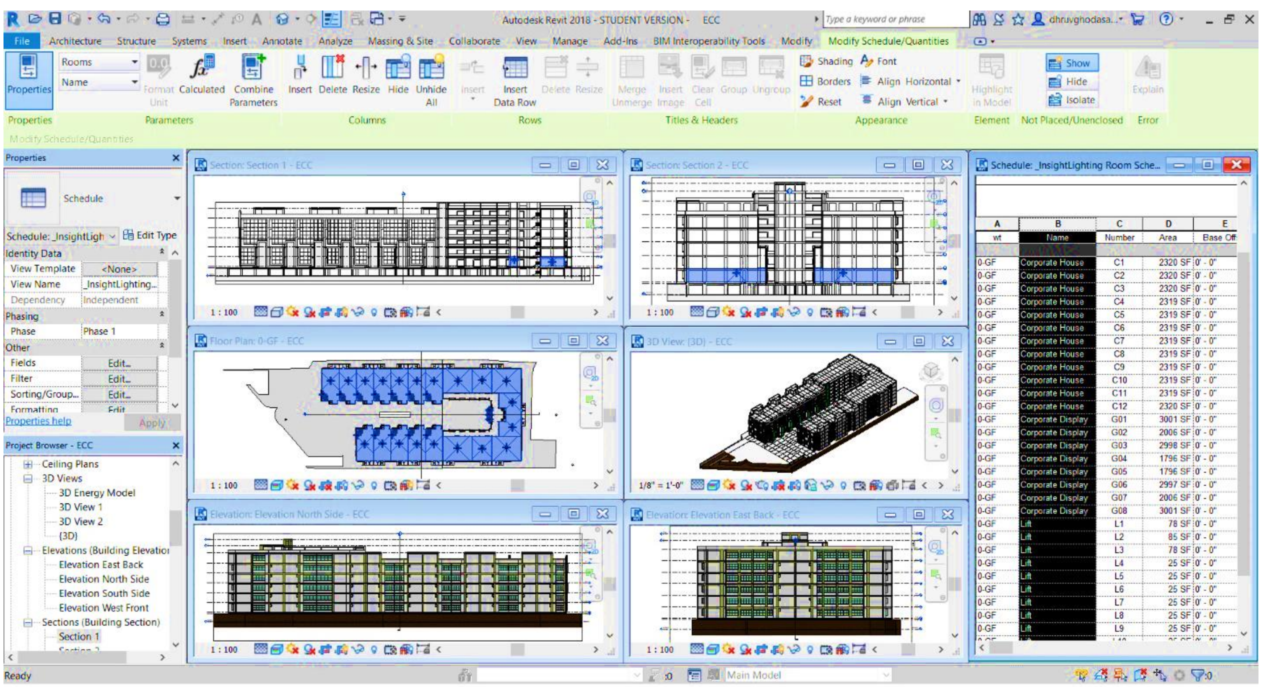

Fig. 3. Working with BIM as the integration of sectional details, floor plans, elevations and schedules

5.2. Identification of mismatched geometry in traditional 2D drawings

The creation of a BIM has revealed that some areas of the building failed to line up when the two-dimensional drawings. AEC agreed that through BIM the maintenance of geometric records will be accomplished in a more efficient way from both economic and quality perspective. In Fig. 4. Geometric mismatch in 2D CAD drawing is identified and indicated with a blue circle.

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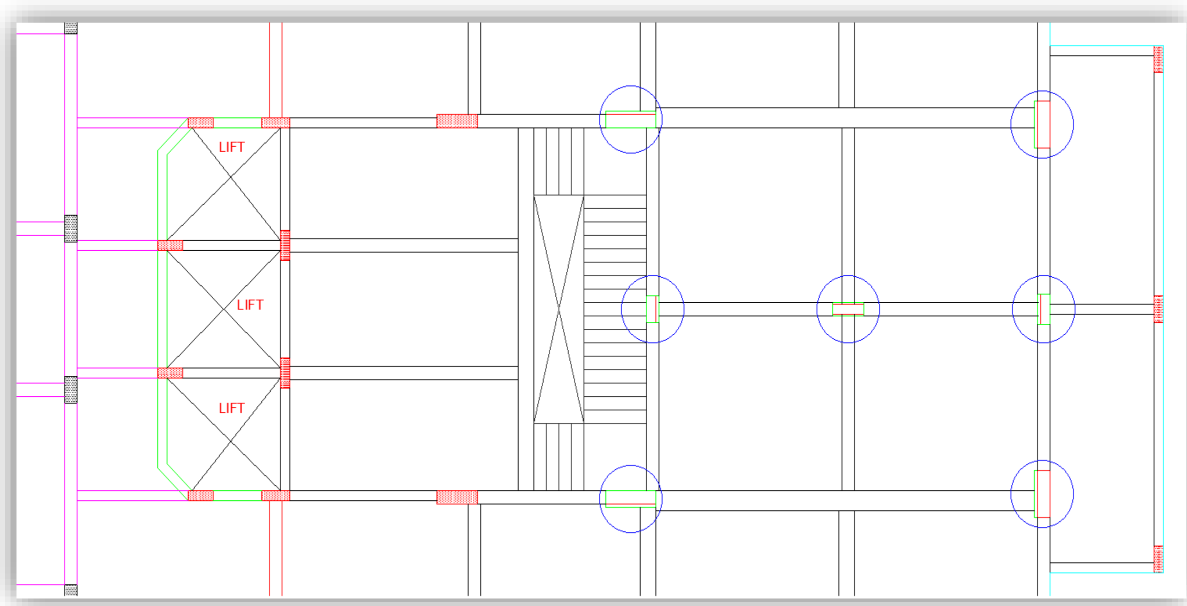

Fig. 4. Mismatch in geometry identified after implementing BIM (Indicated with blue circles)

5.3. Implementation challenges derived from questionnaire and interview

Once the aspects of a case study had demonstrated the application of BIM in FM discussed with the AEC and understanding of the challenges associated with migrating from current FM processes to BIM-based processes. Several implementation challenges were identified as follows:

- The FM staff must also have the skills to be in the position of understanding, maintaining and controlling the BIM. A concise BIM for FM specification must be developed to define the information required to suit the particular requirements of the business and FM functions.
- It was also acknowledged that there are still industry-wide challenges related to technologies and processes. FM professionals wishing to implement BIM for FM in the immediate future should be willing to adapt to such challenges.
- One of the major concerns was the limited compatibility between BIM technologies and FM technologies which can be exacerbated by the huge difference amongst the lifecycle of updates of BIM technologies, FM technologies, and buildings. This means that data standards and interoperability will remain critical for the adoption of BIM for FM technologies in the mid and long term.
- It was also identified that due to the evolving nature of the BIM for FM field, and the differences in the lifespans of technologies, FM organizations must not fit their FM business processes to suit a particular technology which would otherwise result in a continuous effort of adaptation.

FM organizations can presently attain the benefits of BIM for FM through the development of a personalized BIM specification and templates that suit their particular business requirements. It has been found on live projects the geometry data on FM models are of a lower level of development, it is necessary to update and link particular data to the model time by time. Several consultancy works conducted on BIM for FM projects, especially for existing assets, suggests that the FM data are stored in several disparate databases and is likely to be and methodologies that link BIM to these databases are needed. Therefore, FM organizations wishing to implement BIM for FM in the immediate term should take a long-term view and be willing to work with different standards and information formats.

6. Conclusion

BIM applications have been comprehensively discussed throughout the planning, designing, construction, and operation and maintenance phases. BIM in FM application is still considered as an emerging area of upgradation for AEC associated with building construction industry. The challenges and value-adding potential of BIM in FM has to be understood in an early stage of any project for successful implementation. To explore these areas, a literature review and a real-life case study were used in this research. The adoption of BIM in building construction industry will lead to greater productivities through increased collaboration between AEC which helps FM professionals in planning and providing better services throughout the life cycle of the project. The application of BIM in many aspects of Building operations and maintenance can result in more sustainable, efficient and well-managed buildings. It is also found that the amount of data required varies from stage to stage over the lifecycle of the building. The importance of graphical information decreases once the design is complete, while attribute data become more important during the construction and operation phases. So having more accurate data from the early project phases bring in long-term benefits in the operational phase, expanding into shorter response time, improved effectiveness and productivity.

It is also found that BIM for planning and designing is better understood while the value for BIM in construction, and operation and maintenance phase has yet to be demonstrated for a building construction industry. A BIM in FM should meet the requirements of a building owner, meaning that clients need to understand and articulate their BIM requirements including the level of detail needed. A further improvement in this area is to develop specifications for the successful implementation of BIM in FM for a building construction industry as there is a need for a higher level of development during the execution phase. Proper guidelines for LOD will also help in operating and managing facilities for a whole lifecycle of a building thus FM organization is in need of a more automated data management tool and is potentially suitable for BIM implementation.

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Assessing Workers' Perceived Risk During Construction Task Using A Wristband-Type Biosensor

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Abstract

The construction industry has demonstrated a high frequency and severity of accidents. Construction accidents are the result of the interaction between unsafe work conditions and workers' unsafe behaviors. Given this relation, perceived risk is determined by an individual's response to a potential work hazard during the work. As such, risk perception is critical to understand workers' unsafe behaviors. Established methods of assessing workers' perceived risk have mainly relied on surveys and interviews. However, these post-hoc methods, which are limited to monitoring dynamic changes in risk perception and conducting surveys at a construction site, may prove cumbersome to workers. Additionally, these methods frequently suffer from self-reported bias. To overcome the limitations of previous subjective measures, this study aims to develop a framework for the objective and continuous prediction of construction workers' perceived risk using physiological signals [e.g., electrodermal activity (EDA)] acquired from workers' wristband-type biosensors. To achieve this objective, physiological signals were collected from eight construction workers while they performed regular tasks in the field. Various filtering methods were applied to exclude noises recorded in the signal and to extract various features of the signals as workers experienced different risk levels. Then, a supervised machine-learning model was trained to explore the applicability of the collected physiological signals for the prediction of risk perception. The results showed that features based on EDA data collected from wristbands are feasible and useful to the process of continuously monitoring workers' perceived risk during ongoing work. This study contributes to an in-depth understanding of construction workers' perceived risk by developing a noninvasive means of continuously monitoring workers' perceived risk.

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Keywords: Type your keywords here, separated by semicolons ;Construction Safety, Perceived Risk, Wearable Sensor, Electrodermal Activity, Supervised Learning

1. Introduction

Despite continuous efforts to reduce construction accidents, safety in construction still lags behind other comparable industries in most countries. For example, in the United States, there were 971 fatal occupational injuries in the construction industry in 2016 [1]. While the construction industry hired 4.3% of employees, it accounted for more than 18% of total work-related deaths in 2017 [1]. Also, there were more than 1,981,000 nonfatal occupational injuries and illnesses in the construction industry, with an incident rate that is 10% higher than the national average incident rate in 2017 [2]. In Korea, the construction industry reported 579 fatal occupational injuries with a fatal incident rate 3.2 times

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higher than the national average [3]. Furthermore, the poor performance of safety in the construction industry has been a significant issue in other areas including Europe [4], Asia [5], and Australia [6] as well.

Accident investigations have revealed that construction accidents are caused by the interaction between unsafe conditions (i.e., physical environment that contains potential hazard) and unsafe behaviors (i.e., actions that deviate from the safety procedure) [7]. When construction workers are exposed to an unsafe condition, they determine their response to the risk (i.e., safe or unsafe behavior) by comparing the perceived risk with their internal acceptable risk [8]. As such, risk perception is the process in which unsafe conditions interact with workers' safety decision-making processes, which ultimately results in safe or unsafe behaviors. In this regard, there have been continuous efforts to assess workers' perceived risk in construction sites. Such efforts have mainly relied on workers' subjective answers to a set of fixed questions (i.e., survey) [9]. However, these methods are not capable of capturing changes in workers' perceived risk over time because it is almost impossible to conduct the survey at every change in perceived risk. Considering the dynamic nature of construction sites, capturing changes in perceived risk is critical to understand workers' perceived risk. Also, since answers to the questionnaire rely on imprecise memory and the reconstruction of feeling in the past, these methods may be subject to biases [10]. Finally, participating in the survey could interfere with workers' ongoing work because subjects must devote time and energy to answering the questions. For these reasons, there has been increased attention to continuous, objective, and non-intrusive methods to assess workers' perceived risk in construction sites [11].

Recent advancements in wearable biosensors, which can continuously collect an individual's physiological signals [e.g., Photoplethysmography (PPG), Electrodermal activity (EDA), Skin Temperature (ST)], has immense potential to overcome the limitations of the survey-based method. Since physiological signals are affected by the sympathetic nervous system which can be aroused by perceived risk, changes in physiological signals could be indicative of an individual's perceived risk. As such, physiological signals collected from wearable biosensors can be used for continuous, objective, and non-intrusive assessment of construction workers' perceived risk during their ongoing work. Despite such potential of physiological signals acquired from wearable biosensors, their capability to assess workers' perceived risk remains questionable.

To bridge the knowledge gaps, this study aims to develop a framework that recognizes workers' perceived risk based on signal processing and machine learning techniques using physiological signals collected from wearable biosensors during workers' ongoing work. Among diverse physiological signals, this study focuses on EDA, which refers to electro properties of the skin, because EDA is the only physiological signal related to the sympathetic nervous system that is not contaminated by the parasympathetic nervous system [12]. In this study, the authors extracted relevant time and frequency domain features in EDA signals collected from construction workers' wearable biosensors while working on the real construction sites. Then, several supervised learning algorithms were applied to select the best classifiers to recognize workers' perceived risk while working on activities with different risk levels.

2. Perceived Risk Recognition

Figure 1 shows an overview of an EDA-based perceived risk recognition procedure developed in this study. The first step is to collect EDA signals from wearable biosensors. At the same time, workers' activities are recorded to label risk levels of the activities. The second step is to remove the artifacts included in the signal and to decompose the EDA signal into tonic [i.e., Electrodermal Level (EDL)] and phasic component [i.e., Electrodermal Response (EDR)). After removing the artifacts and decompose the signal, time EDL and EDR features in time and frequency domains are extracted. Then, the authors applied several supervised learning algorithms [i.e., Decision Tree (DT), Logistic Regression (LR), Gaussian Support Vector Machine (GSVM), K- Nearest Neighbor (KNN), Subspace KNN (SKNN), and Banging Tree (BT)] to identify the best classifier to recognize workers' perceived risk during their ongoing work. Details of each step in the developed framework will be demonstrated in the following sub-sections.

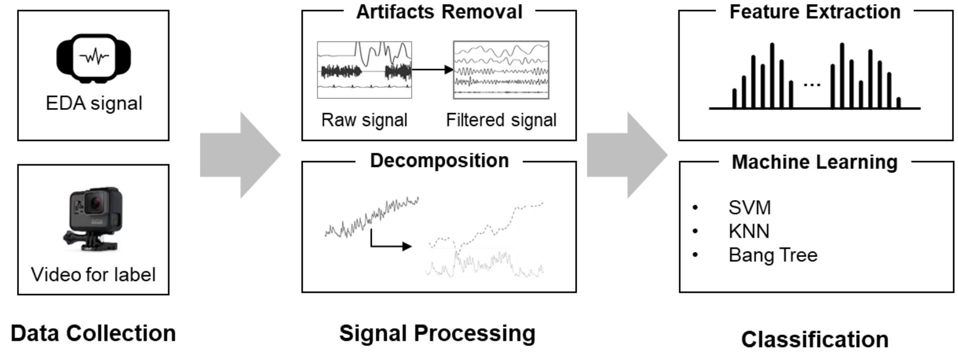

Figure 1. Perceived Risk Recognition Framework

2.1. Data Preprocessing – Artifacts Removal and EDA Decomposition

EDA signals collected by a wearable sensor from construction sites contain a large number of artifacts. An artifact is defined as any variation in the recorded signals that does not originate from the signal source of interest [13]. Artifacts removal is critical to recognize workers' perceived risk because artifacts distort the original signals and skew the analysis [13]. A second-order high-pass filter (cut-off frequency f_c= 0.05 Hz) is applied to alleviate the artifacts low-frequency noises (e.g., noises introduced from variations in temperature and humidity). Also, moving average filter is applied to mitigate high-frequency noises caused by excessive movements and electrode popping, and adjustment of sensors[14].

As aforementioned, EDA signals can be categorized into tonic (i.e., EDL) and phasic (i.e., EDR) components. EDL represents slow changes in the signal which shows baseline drift. EDR refers to short-term changes in EDA signals that reflect an immediate response to external stimuli. To decompose EDA into EDL and EDR, the authors apply the convex optimization method [15]. This method takes apart EDL and EDR from Noisy EDA based on prior knowledge about patterns of EDL and EDR.

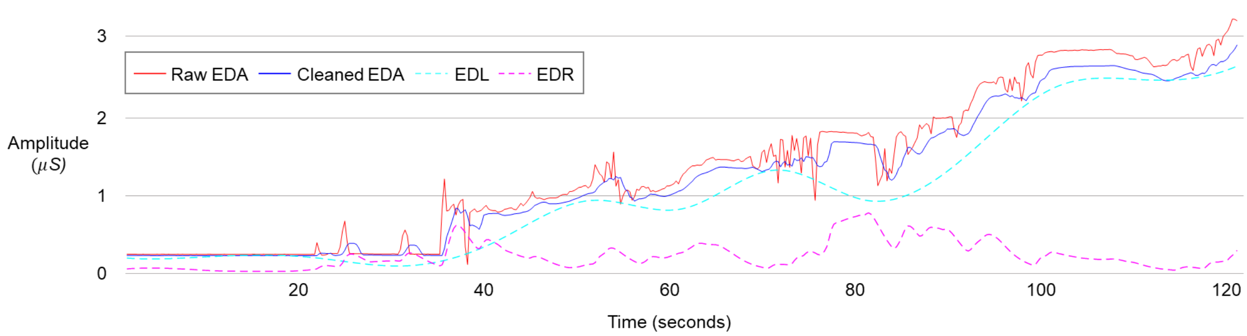

Figure 2. Data Pre-processing: Artifacts Removal and Decomposition

2.2. Feature Extraction

After removing artifacts and decomposing the EDA signals, the authors extracted features that have been used in the literature to recognize the EDA signal patterns reflecting individuals' physiological response to the external stimuli. To extract features, time-series decomposed signals (i.e., EDL and EDR) are segmented using 10 seconds blocks with 9 seconds overlapping (i.e., 1-second moving). The window size is set to 10 seconds considering time lags between the external stimuli and physiological responses. From the blocks of 10 seconds, the authors calculated eight time-domain features and three frequency-domain features. Since EDR reflects immediate responses to external stimuli, features are mainly extracted from EDR but several features from EDL are included because EDL shows general changes in EDA signals that can vary across individuals. Table 1 shows the extracted features in this study.

Table 1. Selected Features in time and frequency domain

Domain	Features
Time domain	Standard deviation of EDR, Median of EDR, Integral of EDR, Normalized average power of EDR, Normalized root mean square of EDR, Mean of EDL, Standard deviation of EDL, Median of EDL
Frequency domain	Spectral power of band 1 (0.1Hz ~ 0.2Hz) of EDR, Spectral power of band 2 (0.2Hz ~ 0.3Hz) of EDR, Spectral power of band 3 (0.3Hz ~ 0.4Hz) of EDR

2.3. Classification

With the extracted features, several classification algorithms are tested to select the best classification algorithm. First, DT, LR, GSVM, and KNN, which have been used in previous studies to detect sympathetic arousal, are tested. In addition, the authors tested two ensemble classification algorithms (i.e., BT, and SKNN) that can facilitate a more accurate performance than their non-ensemble counterpart (i.e., DT, and KNN). To select the best classification algorithm, the tested algorithms are compared in terms of test accuracy. Specifically, data is first undersampled to make the two classes (i.e., high risk and low risk) balanced. When the EDA samples are imbalanced, which means that the number of samples of one class is much more than that of other class, the resultant classifier tends to be inaccurate for predicting the minority class. To avoid such a problem, the majority class is randomly undersampled to make the two classes have the same number of samples. Then, the undersampled data is randomly divided into 80% training session and 20% testing session without overlap. Using the training session, classifiers are trained, and then the trained classifiers' accuracy is calculated by counting how many samples in the testing session are correctly classified by the trained classifiers. This undersample-train-test procedure is repeated 20 times and accuracy is averaged to ensure that the resultant accuracy shows the general performance, not the performance in a randomly generated subset.

3. Field Data Collection

To examine the feasibility of the developed framework in recognizing workers' perceived risk, a field data collection is conducted. EDA signals are collected from eight workers during their ongoing work. All subjects are male and reported no physical and mental disorders that can affect their daily activities. Before starting the data collection, all subjects are informed about the data collection procedure and asked to provide their information including age, gender, height, weight, work experience, and trade. Table 2 summarize demographic information of the subjects.

Table 2. Demographic information of the subjects

Domain	Age (years)	Height (cm)	Weight (kg)	Work Experience (years)
Mean	32.37	181.5	88.88	10.25
Standard Deviation	8.57	7.14	12.92	6.72

After providing the demographic information, all subjects are asked to wear a wristband-type biosensor to collect EDA data during their ongoing work. After wearing the sensor, subjects are asked to perform their daily work. At the same time, subjects' activities are video recorded using an action camera to label the activities at different risk levels (i.e., low-risk and high-risk). Each worker participates in the data collection during half of their working hours. The data collection procedures are approved by the IRB (Internal Review Board) of the University of Michigan. After the data collection, two research team members, who have expertise in risk related to construction activities, separately classify all subjects' activities into low-risk activities and high-risk activities using the recorded video. Figure 2 shows the wristband used in the data collection and examples of low and high-risk labeled activities in the data collection. In the case of inconsistency in the results of the label between two members, the data were excluded in the analysis to improve the reliability of the analysis. The labeled data are used to learn the machine learning model and evaluate the performance of the classifiers.

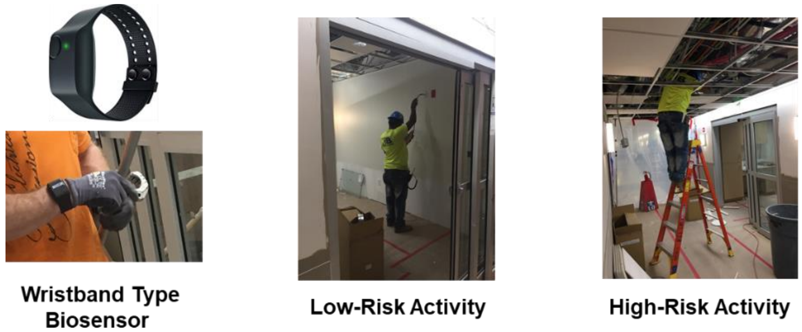

Figure 3. Wristband and Examples of Data Labelling

4. Results and Discussion

As aforementioned, six classification algorithms are compared. The accuracy indicates the algorithms' overall performance to correctly classify the EDA samples. Table 3 shows the test accuracy of the tested algorithms. As a result, KNN showed the best accuracy, 76.9%. Since KNN, which does not learn a decision boundary based on parametric models, outperformed other parametric algorithms such as LR and GSVM, this result indicates that the data is hard to classify by parametric models in the given dimension (i.e., 11 EDA features). When additional features that can help to separate the two classes are added, the parametric algorithms might be able to outperform KNN.

Table 3. Classification accuracies of each tested algorithm

Algorithm	DT	LR	GSVM	KNN	BT	SKNN
Accuracy	69.1%	61.7%	73.2%	76.9%	76.4%	71.8%

In addition to the accuracy, the authors computed precision and recall to investigate whether the classifiers are biased to accurately work for only one class. Precision shows the performance of the classifier to exclude actual low-risk samples from high-risk class, while recall shows the performance to include actual high-risk samples in high-risk class. Since the data was first undersampled to make the two classes have a sample number of samples, the prevision and recall of the tested algorithms were quite close to accuracy as shown in Table 4. However, recall is generally higher than precision throughout all the tested algorithms. This may be explained by the limitation of the labelling method. Since research team members labelled the level of risk based on the research team members' subjective evaluations based on the recorded video, if the subjects perceived high risk by other stimuli that were hard to be captured by video (e.g., risk factors that are visually perceived by the subjects, but out of video angle), actually high risk samples can be mislabelled as low risk.

Table 4. Confusion Matrices

DT		True Class		Precision	Recall
		High Risk	Low Risk		
Predicted Class	High-Risk	41,223	19,900	67.4%	73.7%
	Low-Risk	14,677	36,000		

KNN		True Class		Precision	Recall
		High Risk	Low Risk		
Predicted Class	High-Risk	44,664	14,580	75.4%	79.9%
	Low-Risk	11,236	41,320		

LR		True Class		Precision	Recall
		High Risk	Low Risk		
Predicted Class	High-Risk	37,242	24,211	60.6%	66.6%
	Low-Risk	18,658	31,689		

BT		True Class		Precision	Recall
		High Risk	Low Risk		
Predicted Class	High-Risk	46,017	16,552	73.5%	82.3%
	Low-Risk	9,883	39,348		

GSVM		True Class		Precision	Recall
		High Risk	Low Risk		
Predicted Class	High-Risk	43,471	17,557	71.2%	77.8%
	Low-Risk	12,429	38,343		

SKNN		True Class		Precision	Recall
		High Risk	Low Risk		
Predicted Class	High-Risk	41,106	16,782	71.0%	73.5%
	Low-Risk	14,794	39,118		

5. Conclusion

This study examines the feasibility of using physiological signals (EDA) acquired from a wristband type biosensor to recognize construction workers' perceived risk at construction site by applying signal processing methods and developing a machine learning model. To select the best classifier, this study evaluates the performance of several supervised learning algorithm (i.e., DT, LR, GSVM, KNN, SKNN, and BT) in recognizing workers' perceived risk during their ongoing work. KNN shows the best performance with an accuracy of 76.9%. The results show that features based on EDA signals have capability to recognize construction workers' perceived risk while working under different risk levels (i.e., low and high-risk activities) at real construction sites. The results contribute to an in-depth understanding of construction workers' perceived risk by developing a non-invasive means of continuously monitoring workers' perceived risk. The proposed framework can contribute to improving construction safety continuously monitoring of workers' perceived risk during their ongoing work. Further research should be conducted to optimize the performance of the framework by comparing different window sizes and including features extracted from other physiological signals such as PPG and ST.

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Augmented reality application supporting on-site secondary building assets management

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Abstract

Secondary building assets management requires a large amount of information related to them. Nevertheless, building assets surveys are cost and time demanding, especially because they need long post-processing efforts in order to systematize collected data. Furthermore, with the recent transition towards the BIM methodology for building management also modeling building objects both in their geometric features and in their related information is a long process and error-prone task. Under these circumstances the possibility of performing the majority of operation on-site would definitely make the process more efficient and it would reduce errors. Augmented Reality (AR) with its capability of overlapping digital data to the real scene is the right tool to support operators on-site.

The proposed system has the aim of reducing the time of secondary building assets survey and provide a tool for the automatic enrichment of BIM models. An AR device (Hololens) with an embedded computer and a neural compute stick constitute the portable on-site system for the automatic recognition of assets objects, removing the necessity of reworking data off site. A trained Deep Learning Neural Network inside the neural compute stick performs the recognition providing the operator with objects features and position. The AR application inside the Hololens operates as an interface between the user and the digital information just created. Finally, data is stored in a NoSQL database linked to the BIM model so as to be available for further operations. The visually supporting information provided by the AR tool, the possibility of working on data directly on site and the portability of the system represent means for increasing efficiency in survey operations. First tests have been conducted so as to prove the feasibility of the system and its use on site without further equipment.

Keywords: Augmented Reality; BIM; Facility Management; Building asset.

MR	Mixed Reality	AI	Artificial Intelligence
AR	Augmented Reality	AIM	Asset Information Model
NN	Neural Network	FM	Facility Management
BIM	Building Information Model		

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1. Introduction

Information management represents a big challenge in the AEC industry especially during buildings operational phase [1, 2]. The cost of information is doubling since it is paid once during the project and after during the building lifecycle to retrieve all the necessary data, which can also be not available, mainly in existing constructions [1, 3, 4]. A number of techniques and technologies are now in use, including EDM (Electronic Distance Measurement), GPS (Global Positioning System), 3D Laser scanner [5]. However, each of the aforementioned technologies requires further post processing of data in order to provide interpretation. On the other hand, BIM is spreading as a standard for information management. For this reason, even Facility Management (FM) is expected to be based on an Asset Information Model (AIM) populated from the BIM model which would play a beneficial role in many FM practices [6]. Anyway, data is still often collected manually while the digitization that the construction industry is facing in recent years has led to a growing interest in one of the major benefits of this change: the automation of processes. For the reasons stated above with this research we propose a system that exploits the advantages of different technologies such as Mixed Reality, BIM and Neural Network with the aim of reducing post-processing effort in the interpretation of data thanks to the automation of some processes and an efficient human-machine collaboration.

2. Scientific Background

Building surveys still demand high costs and time to be pursued since, despite the high accuracy achieved by the latest techniques, such as laser scanning and photogrammetry, much of the work is still done post processing. Among the latest procedures proposed Adan et al. presented a method for the detection of ‘small components’ such as fire extinguishers, switches, sockets and signs [7] through 3D laser scanned point clouds. On the other hand, Lu et al. [8] recognize and model building structural components with a combination of three sub-systems: 1) object recognition, based on a new neuro-fuzzy framework; (2) material recognition, based on image classification procedures; (3) IFC BIM object generation. All of the aforementioned methods still require a post processing effort and data interpretation pursued off site without the possibility of checking or adding missing information. Bonanni et al. [9] proposed a method that works on site combining a robot, which employs a SLAM (Simultaneous Localization and Mapping) module for building up the map of the environment, and human input to provide spatial hints about entities of interest. This solution is still laborious since the operator has to manually detect the object and enter its features. On the other hand, MR has already demonstrated its potentiality in supporting operations on buildings [10] displaying information through holograms which is a much more convenient way to bring data on site [11]. One example of this is represented by Ammari et al. [12] who developed a system capable of showing holograms thanks to Augmented Reality (AR) and image tracking. Kopsida and Brilakis [13] present an evaluation of different methods that could be implemented for a marker-less mobile BIM-based AR solution for inspections, concluding that there are no efficient mobile AR solutions for on-site inspections and that other methods for marker-less AR, even if already introduced, have not yet been tested on construction sites.

Lastly in recent years there have been already done tests about the combination use of Neural Network (NN) and Augmented Reality together. Baek et al. [14] proposed a NN-based method for indoor localization with the purpose of providing relevant information in FM applications. Nevertheless, many issues have still to be addressed: the proper scale of the visualization of building components in situ; accurate localization of the operator inside the building so as to automatically display relevant information; recognizing building assets without specific markers (visual markers or RFID tags); and providing an effective interface between MR headsets and BIM data.

3. Secondary building assets survey

The system proposed has been specifically thought for the use case of secondary building assets survey. The inventory is a costly operation [2] since it requires a large amount of money and thousands of man-hours for creating/updating information [3, 4] necessary for operating buildings. Current inventory procedures still require long post-processing [15], while the system proposed aims to reach a certain level of automation in the process of data collection improving the efficiency and leading to an automatic enrichment of BIM models.

The system presented with this research proposes a new survey procedure. The operator wears the MR head-mounted display and walks into the building for the first time. The recognition application developed is able to recognize secondary components just framing the objects. The snapshots of the Hololens is sent in real time to an embedded system where NN carry out the recognition process whose result is a label associated with a bounding box that contains the recognized object. The label is the piece of information that the application uses to choose a specific object among a predefined library. The bounding box, which is defined by the x,y coordinates of its center plus width and height, is used to place the object, as a hologram, into the real environment. When the application is not able to recognize the object there is still the possibility of adding it manually in the correct position. At the end of the survey all the data and positions of the detected objects are transferred into a NoSQL Database so as to be available for future operations.
One of the most valuable advantages of this procedure lays in the checking real time the collected data with the possibility of modifying them if necessary directly on site. This will reduce the possibility of incorrect or missing data since all the survey operations are accomplished on site, avoiding a post interpretation that is an error prone procedure. On the other hand, the AR feature of displaying the gathered information overlapped to the real world make it easier to interact with them. In contrast with current methods where there is a prevalence of machine-human working in series the proposed method will lead to a machine-human work in parallel system reaching a higher efficiency.

4. Recognition system components

The system components can be grouped in two different environments: the MR environment which is where the digital copies of the real objects are developed including the object recognition application explained in the following paragraph and the real environment which is represented by the building and the assets object of the survey, the operator and his whole equipment. The MR environment is composed of the following components (Figure 1):

- BIM environment used to develop the initial building model.
- The MR platform (Unity software) that allows to develop applications for the MR tool.

The real environment, on the other hand, comprises the following elements (Figure 1):

- Microsoft Hololens which is the MR head-mounted display. It acts as an interface between the digital world and the real world (operator and environment).
- On-site operator who is doing the survey wearing the Hololens and the embedded system.
- Neural Computer Stick-Movidius which is specially designed for working with neural networks. In order to make the entire system usable on site the images are processed by this tool, as opposed to rely on cloud computation.
- Embedded PC- Raspberry which works as an interface between the Hololens and the Movidius, and as a hardware support for the latter.

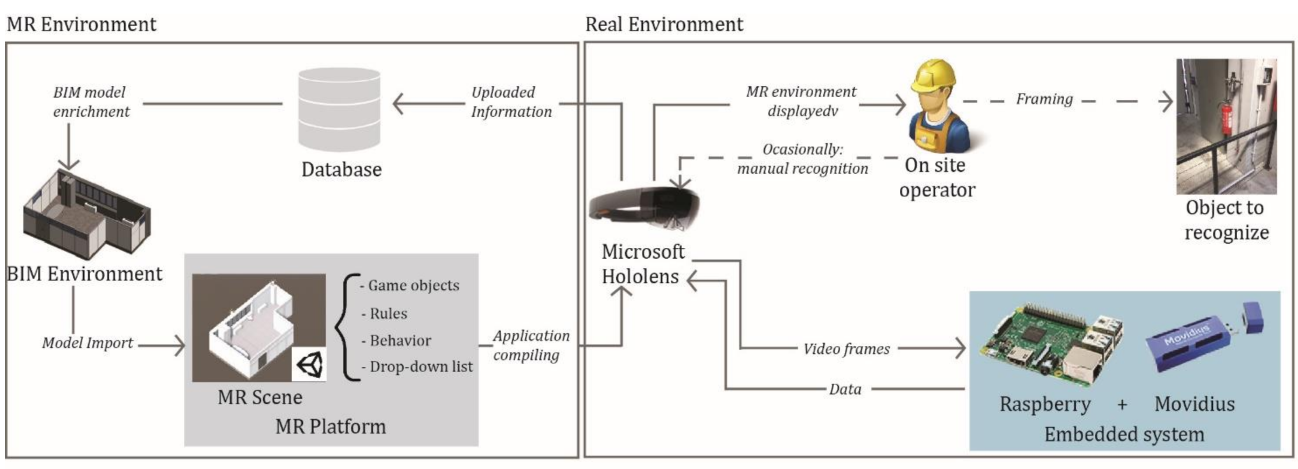

Figure 1 - System components

4.1. Recognition application

The recognition application will be developed in Unity, using the programming language C#. This application will carry out the following tasks:
1.to read and interpret the data about the position of the operator inside the building, and therefore in its digital twin;
2.to send the snapshots to the embedded system;
3.to read the data from the recognition process (bounding box coordinates and object type);
4.to identify among a predefined library of objects the object type that matches the recognition response;
5.to locate the object in the right position according to the bounding box coordinates provided in the recognition response and the depth dimension provided by the mesh (that Hololens automatically does because the fire extinguisher owns a behavior for its positioning on walls);
6.to provide the possibility of modifying the object type or its position manually;
7.to provide the possibility of adding objects manually.
Tests on the insertion of doors and windows in the MR environment have been carried out.

4.2. Neural network

Neural Networks represent the method chosen for the recognition of small objects. In order to perform the recognition with NN it is just necessary to frame the object; this simplicity in their usage make their use on site fast and instinctive. For our purposes the NN not only has to recognize the correct type of object but also its position within the frame, so as to make it possible its positioning in the real environment. Among all the types of neural networks that exist the YOLO, which are able to perform classification and localization in one-step, is the one chosen for this project. This choice depends upon the speed of this kind of NN which is 45 frames per second; making the snapshots processed in real-time, with negligible latency of a few milliseconds. Furthermore, the YOLO can predict multiple bounding boxes and scores simultaneously. Finally, they are an open source solution [16, 17]. In this project, a pre-trained YOLO is used. In order to customize the recognition process it is possible to re-train the last level of the network. The creation of the necessary dataset of images to train the network for our purpose is explained in the following sub-section.

4.2.1. Fire extinguisher datasets

The dataset to train the network should have specific features and it has to include at least one image for every existing type of object (fire extinguisher in this case), so as to be able to recognize it no matter the external appearance. The more the number of images the better the network will train. For this reason, the dataset will be made up of both original pictures and graphically re-edited photos as suggested by studies on dataset creation [18]. The creation of the dataset involves also labelling all the images and drawing the bounding box around the object to be recognized. For this operation we worked using Visual Object Tagging Tool. The output of this process is a .txt file for each image with a line declaring the class and the bounding box coordinates (X,Y of the center and width and length). Our first tests aim to recognize only the object, but next steps will handle the recognition of different fire extinguisher type. It is likely that for this purpose the distinctive components of the fire extinguisher (pressure gauge, horn) need to be recognized separately to help in defying the type.

4.2.2. Neural network training

A tiny YOLOv2 pretrained with the COCO dataset was chosen for the first training session. To train the network the following files are required [18, 19]: a file containing all classes labels (1 for our case); a text file with the path to all the images basis of the training; a text file containing all the paths to the previous files; a configuration file with all the layers of YOLO architecture and finally pre-trained convolutional weights. The original *.cfg* file has been modified as follows for our customized training: 1) batch=64, this means we will be using 64 images for every training step; 2) subdivision=8, the batch will be divided by 8; 3)classes=1, the number of categories we want to detect; 4) filters=30, this come from this formula filters=(5+number of classes)×number of bounding box in each grid cell of the image; 5) learning rate=0.001, advised by the developer of YOLO in order to avoid false minimum point. After the training session, the new *.cfg* and weights files are created.

4.2.3. Neural Network testing

First tests about the training of the Neural Network have been carried out on a computer in this preliminary phase. The YOLO tiny v2 chosen has been trained with three different datasets as follows:

The three datasets are composed as follows:

• DATASET 1 (D1) =300 images, 75 (25%) original taken inside the Engineering Faculty premises (Polytechnic University of Marche), 225 (75%) obtained through the augmentation process;

• D1 added to DATASET 2 (D2) = 200 images, 50 (25%) original downloaded from Flickr (only images of fire extinguisher meeting the requirements expressed in the paragraph 5.4.1), 150 (75%) re-edited images;

• D1 and D2 added to DATASET 3 (D3) = 200 images, 50 (25%) original taken inside the Economic and Science Faculties (Polytechnic University of Marche), 150 (75%) re-edited images.

For every dataset the images were divided into two groups, one for the training (75%) and one for the test (15%). The kind of chosen images was similar for all the photos, close-up and with the object entire and placed in the center (Figure 4). The reached mean average precision (mAP) was 60,23% in the first case. The second training counts 86700 iterations and in this case the mAP was 61,54%. In the final training the number of iterations reached 26900 with a mAP of 62,81%. The validation tests have been conducted for each of the three training sessions with the third training dataset. The percentage of fire extinguisher identified started from 38% and reached 45% with the latest training. the precision improved too because while in the first case 26 false positives occurred, in the latest case the number decreased to 14.

4.3. Embedded system

The embedded system is composed by the Neural Compute Stick Movidius and a Raspberry and its aim is to have all the necessary components for performing the survey directly on site. This will make the system self-sufficient and portable in every working situation.

4.3.1. Data transfer from Hololens to computer

Each frame captured from Hololens camera video stream is sent to Raspberry. Single frames are preferred to video stream for the following reasons: i) it's easier to associate each photo with its 3D-information obtained at the instant of the shot; ii) no need for the support of Real Time Protocol required by video streaming; iii) neural networks input for object recognition are single frames. Each frame captured by the Hololens goes through the following steps: i) sending pre-processing; ii) sending; iii) receiving; iv) sending post-processing; v) pre-processing for neural networks; vi) neural network inference; vii) send back NN output to Hololens. Steps (i) and (iv) could be jpeg-compression, cropping and/or scaling. Steps (v) depends on the NN. Exchanging data between Hololens and Raspberry required the development of a custom socket over a Wifi network between Raspberry (hotspot) and Hololens (client). The socket could be either TCP or UDP. Table 1 shows possible configurations. Data rate is the worst, 30 MBps, its measured range is about 50 ± 20 Mbps (uncertainty is due to unmanageable environment variables in both TCP or UDP socket).

Table 1 - Performance tests, each one elaborate 150 photo. (a) Total time for sending raw photos (cropping and scaling times are neglected, max 10 ms). (b) cropped from 896x504 photo. (c) scaled from 896x504.

	Size [kb]		Times [ms]			
Resolution	raw	jpeg	encoding	sending	total	total[(a)]
1408x792	3’340	154	94	5	99	111
896x504	1’350	60	46	2	91	45
416x416[(b)]	519(b)	24	29	0,8	46	17
416x416[(c)]	519	32	45	1,1	62	17
416x234 [(c)]	292(b)	23	36	0,8	46	10

4.3.2. Object detection result transfer

The chosen NN YOLOv2 unit is a float number, received frames are in byte format, a pre-processing step, *(v)*, represents the conversion from byte to float. The YOLOv2 input is a 416x416x3 tensor, corresponding to the frames to be processed (416x416 is resolution, 3 is number of float for pixel). The network (loaded on Movidius) processes this input and returns an output of 13x13x[(*C*+5)x5]. The frame is divided in 507 cells of same width and height, for each cell it finds 5 bounded boxes and for each of them it calculates: width, height, horizontal and vertical distance from top left corner; objectiness which is the probability of an object to rely in this bounding box (not a particular type of object, just an object); *C* probabilities indicating the object category in the bounding box. Then it filters bounding boxes with objectiness lower than a fixed threshold and, for the rest ones, filter those object categories having probability lower than an arbitrary threshold. If the purpose is to recognize just fire-extinguisher, the Raspberry sent back to Hololens one bounding box (through the socket) defined by x,y,w,h and the photo id (used by Hololens to retrieve the saved 3d information of the frame to place the hologram in the three-dimensional space). Filtering will take place only in Raspberry to reduce Hololens work. Due to the small size (could be 20 bytes) of Rasp output, sending time could be neglected.

5. Conclusion and further steps

This research aims to provide a support to FM operations during the building lifecycle in order to improve efficiency. Three different technologies are combined together for an on-site use: the AR, the BIM data model and Deep Learning. First feasibility tests have been conducted related to the NN and data transfer. Next steps will include the improvement of NN performances, the recognition of precise type of fire extinguisher and the full development of the AR interface and tests in a real environment.

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Building information modeling (BIM) for safety risk identification in construction projects

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Abstract

A significant number of fatal accidents and injuries are still reported in construction projects worldwide inducing consequent socioeconomic impacts. A crucial factor in construction safety is to properly identify possible hazards at any stage of the construction process. Existing research has not focused much on the automatic detection of risks associated with the inexistence or misplacement of protective safety equipment. This paper presents a method for detecting safety risks (to which workers may be exposed in a construction project) concerning the inappropriate placement or handling of protective equipment. In this approach, the construction site is dynamically modeled employing Building Information Modeling (BIM) technology. In particular, the project status is recorded at regular intervals using a camera. The data provided by the camera are transferred to BIM software and the site plan view is processed via a Matlab pattern recognition module to observe protective equipment misplacement or removal. The software compares the current image with the anticipated safety protection plan of the construction work and automatically detects the safety potential hazards areas along the work area. Within the extracting results, visual representation and labeling of the work areas that present unsafe conditions for the workers are developed and prompt alerts are forwarded to the project supervisor by e-mail specifying the location and type of hazard. The employment of the presented methodology could enable participants in the construction process to promptly identify and restore safety deficiencies, improving thus work safety and minimizing the number and/or the impact of accidents in construction sites.

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Keywords: Building Information Modeling (BIM); work safety; risk identification; pattern recognition; job hazard areas.

1. Introduction

Construction has become one of the most unsafe industries due to the harsh work environment and high risks involved [1]. According to global statistical data, its accident death and injury rates are three and two times higher respectively than the average of other industries [2]. In spite of more attention being paid to safety management in recent years, the accident rate of the construction industry continues to be high. Risks are gradually growing due to the increasing structural complexity, project size, and the adoption of new and complex construction methods [3, 4]. Therefore, improving safety has become an absolute priority.

According to British Standards Institution [5], safety management can be defined as a systematic and comprehensive process for managing safety risk, to provide safe and healthy workplaces, prevent work-related injury and ill health.

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Construction safety management can be divided into the preconstruction stage and construction stage [6]. In pre-construction, potential safety hazards are normally identified based on the safety officers' or project managers' experience and eliminated via safety training and safety planning. During construction, accidents are prevented by monitoring workers and the environment on site [7].

The current approach to construction safety management, summarized as follows:

a) Traditional safety planning is carried out by means of manual observations, which result to be labor-intensive, error-prone, and often highly inefficient. The link between safety planning and work task execution lacks accuracy due to the massive use of two-dimensional (2D) drawings and, not less relevant, the extensive use of software which loses the connection with the real site simulation. Moreover, building designers and Health and Safety (H&S) coordinators still lack a collaborative working approach and the choices of the H&S Coordinator do not affect project design [8].

b) Safety training is traditionally based on indoor teaching, which lacks interaction, intuition and hands-on training, and therefore marginally improves the safety consciousness of workers [9].

c) Safety officers often apply inappropriate site monitoring as they simply use a checklist to manage construction safety by identifying and recording violations. In the absence of technological support, however, it is impractical to monitor the whole site simultaneously due to its large size and dynamic environment [10].

Current research is making some efforts to solve these problems with the help of visualization technology, which makes information digital and visual while depicting the construction environment with contribution to improving construction safety management.

2. Background

2.1 Overview of the literature

There are different research methods that focus on job hazard area identification during design and construction phases. Getuli et al have presented an H&S BIM-based design and validation workflow, specifying the minimum level of requirements and mandatory informative content for the submission of construction site layouts and safety plans, analysing construction phases and identifying potential safety issues in a virtual environment [8]. Shuang et al have presented a framework for systematic personal safety performance and participation assessment through obtaining real-time locations [11]. Hongling et al have introduced a BIM and safety rules integrated approach developed to implement the automated identification of the unsafe factors in design and automatically rectify them to aid in construction safety management on site [12]. S. Zhang et al have investigated how potential fall hazards, which are unknowingly built into the construction schedule, can be identified and eliminated early in the planning phase with a framework that includes automated safety rule-checking algorithms for BIM [13]. L. Zhang et al have presented an innovative approach of integrating BIM and expert systems (B-RIES), composed of three main built-in subsystems (BIM extraction, knowledge base management and risk identification), which is developed to provide real-time support for decision making in traditional safety risk identification process in tunnel construction. [14]. Kim et al have introduced a safety planning platform (implemented in BIM) to simulate and visualize spatial movements of work crews using scaffolding [15]. Computational algorithms in the platform automatically identify safety hazards related to activities working on scaffolding and preventive measures can be prepared before the construction begins. In terms of visualization, a number of works have been reported in the literature regarding construction safety management (e.g. [16, 17]).

Many existing and well-executed studies have focused on risk identification methods mainly at preconstruction stage (design and planning). No practical approaches exist to date on how the data of unsafe conditions can be used by practitioners in order to improve safety during the construction of a project. In this paper, such a methodology is presented, which can enable participants in the construction process to promptly identify and restore safety deficiencies.

2.2 Need for an automated safety checking system

A construction site is a very dynamic environment in which the workspace related to construction activities changes continuously according to project-specific construction data. The planning and design phases provide a vital opportunity to eliminate or mitigate hazards before they appear on-site. Inefficiencies are witnessed in predicting all possible health and safety risks for workers in the project development and operation phases. During project construction, the safe working practices specified in Safety and Health Plan (SHP) and safety construction drawings are not fully implemented, as shown in national and international practice. Visual technology can offer a 3D and automatic approach to identify job hazard areas and potentially play a key role in reducing current incident rates. Vision-based detection of safety risks in real time can resolve safety issues during construction work. Other potential contribution of automated tools to assist safety management in construction is the development of an enhanced framework to facilitate the communication between contractor and designer for safety issues [18].

3. Research method

The proposed methodology for implementing automated rule-based safety checking is illustrated in Fig. 1 and consists of the following elements.

3.1 Image capturing and project data transferring

The methodology starts with capturing the project status at regular intervals appropriately specified (e.g., every 30 minutes). The imaging laser scanner BLK 360 by Leica Geosystems is employed for this purpose. The scanner performs spherical imaging with HDR support. A complete full-dome laser scan, 3D panoramic image capture and wireless transfer to the Autodesk ReCap 360 Pro application takes approximately 3 minutes. In the current application, the scan data are filtered and registered in real-time. ReCap 360 Pro enables point cloud data transfer to a number of BIM applications.

The project site instantaneous image data (taken by the scanners every thirty minutes) are wirelessly transferred to the Autodesk ReCap 360 Pro application. The image focuses mainly on job hazards areas of the project (e.g., warning signs, fences, protective equipment, scaffoldings, excavations, slab edges, portable ladders, holes, construction machinery etc). Then the image data are transferred to Autodesk Revit for better display and processing. The site plan view is inserted as an image from Autodesk Revit to Matlab code with the detection algorithm described below. The file transfer and conversion from tool to tool is done automatically (see Fig.1). Alternatively, the images from a simple camera could be entered into the Matlab code directly, in image file format ".png", without processing by Autodesk Revit.

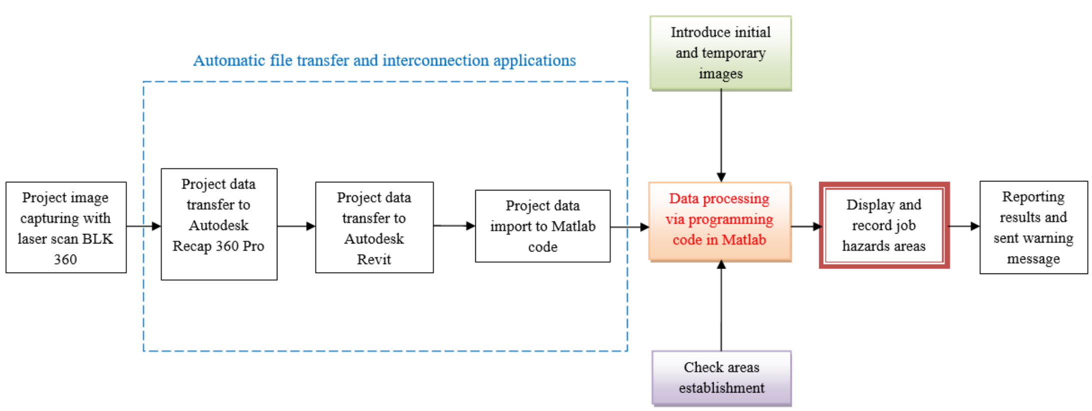

Fig. 1: Automated rule-based safety checking implementation framework

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3.2 Algorithm operation

The algorithm for the detection of job hazard areas in a construction site is developed by a programming code using the application Matlab R2018a. The algorithm operation includes three modules, as illustrated in Fig. 2.

At the upper module ("Data entry"), all necessary information, as original and temporary images, e-mail address and defined check areas, is introduced and recorded at the Matlab code. All the necessary information is introduced by the respective selection from the “options window” of the code. The original image illustrates the ideal safety protection plan while the temporary images illustrate the real conditions over time at the work areas of the construction site. All images are taken from the same optical angle. Each check area is characterized with an integer identification number in ascending order.

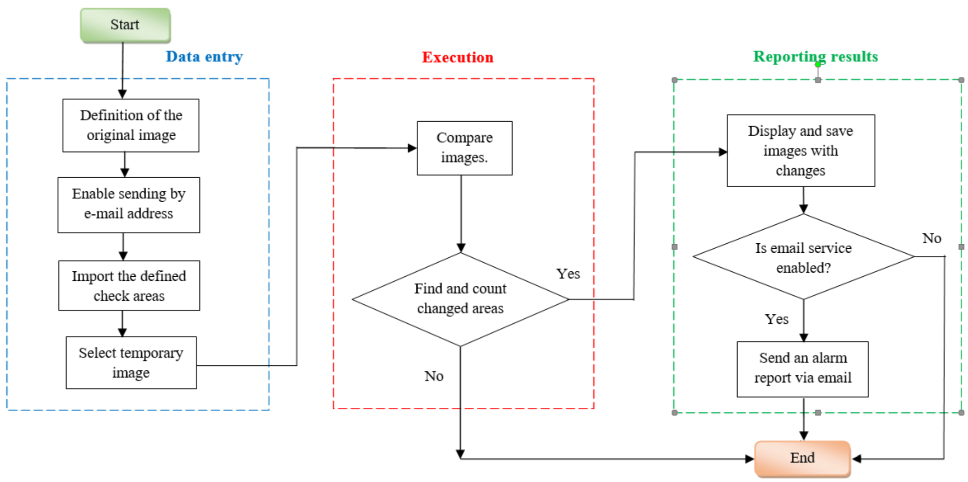

Fig. 2: Illustration of algorithm operation

At the “Execution” stage, the code performs the comparison of the two images (ideal and current) with “pixel by pixel” searching procedure and determination of deviations between the two images. Each image consists of 3,600 pixels on the x axis and 2,580 pixels on the y axis (in total 9,288,000 pixels). Once the execution cycle has completed, the code finds and recognizes the areas of the worksite where there are differences between the images and thus unsafe working conditions.

At the “Reporting results” stage, results from execution stage are displayed, recorded and sorted. Both images are displayed with marked areas where changes have been detected. At the same time, a warning notice is generated to the site manager (or other responsible person), with the respective image, specifying the areas with unsafe working conditions. The notification is automatically transmitted through e-mail electronic message.

Overall, with this algorithm it is possible to determine the type and location of potential risks arising in the construction site. The most noticeable benefit of the process is the capability of automatic and instant notification at any time of the day, which makes immediate problem settlement feasible.

3.3 Case study: applying the automatic work hazard identification process in a roadwork construction site

The typical site (3D view) of the arrangement is shown in Fig. 3 (from Autodesk Revit with file type “png”). The construction work is supposedly carried out along the pavement width and partly on the carriageway. Warning signs, fencing, and safety barriers are required (according to the legislation) to prevent accidents due to the coexistence of workers, machinery, pedestrians and vehicles traveling along the road. In the Figure, one can also see the check areas with numbers in yellow boxes, as they had been defined in the first algorithm module.

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It has been observed that, in such projects, warning signs, fencing, and safety barriers are not typically placed in accordance with the safety standards or are being moved during the project implementation from their proper position to make work easier, at the expense, however, of increased likelihood of accident occurrence. To reduce the frequency or fully avoid such hazardous circumstances, the proposed methodology is used for automatically detecting the lack or misplacement of warning signs, fencing and safety barriers in the work site. Following data entry and code execution, the results are produced in both forms, a report (Fig. 4) with the image frames where differences between the original and current images (in the example frames 26, 27, 44, 45 & 46) and a graphical form of the two images in contrast (Fig 5) with clearly marked deviations.

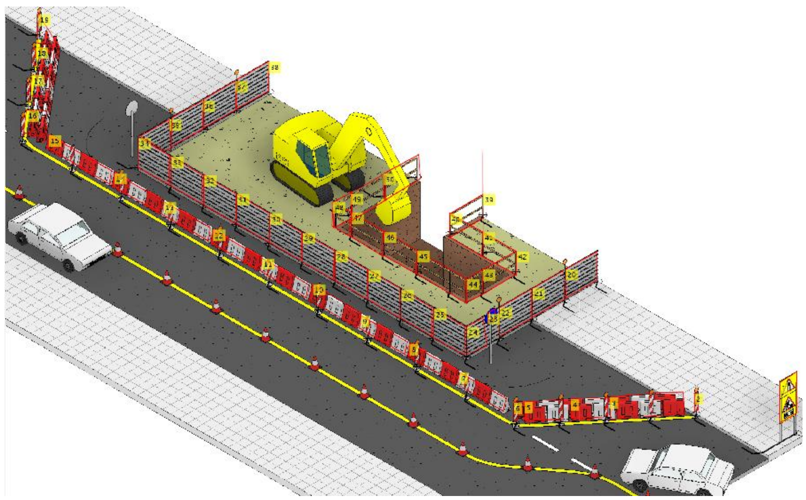
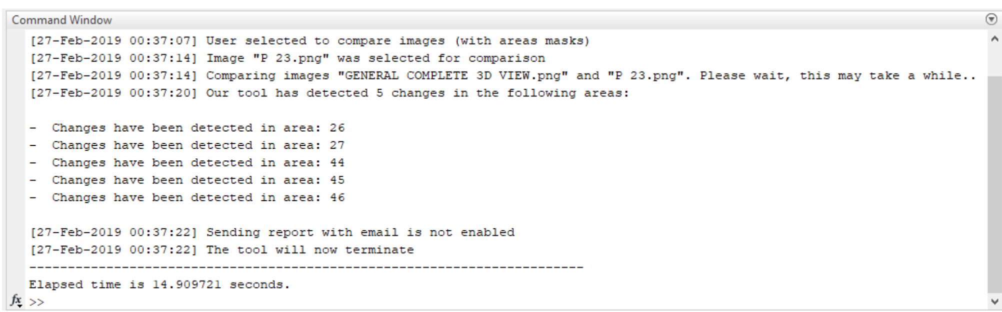


Fig. 3: Site view of the project site with check areas



```
Command Window
[27-Feb-2019 00:37:07] User selected to compare images (with areas masks)
[27-Feb-2019 00:37:14] Image "P 23.png" was selected for comparison
[27-Feb-2019 00:37:14] Comparing images "GENERAL COMPLETE 3D VIEW.png" and "P 23.png". Please wait, this may take a while..
[27-Feb-2019 00:37:20] Our tool has detected 5 changes in the following areas:

-  Changes have been detected in area: 26
-  Changes have been detected in area: 27
-  Changes have been detected in area: 44
-  Changes have been detected in area: 45
-  Changes have been detected in area: 46

[27-Feb-2019 00:37:22] Sending report with email is not enabled
[27-Feb-2019 00:37:22] The tool will now terminate
----------------------------------------------------------------------
Elapsed time is 14.909721 seconds.
fx >>
```

Fig.4: Result report instance

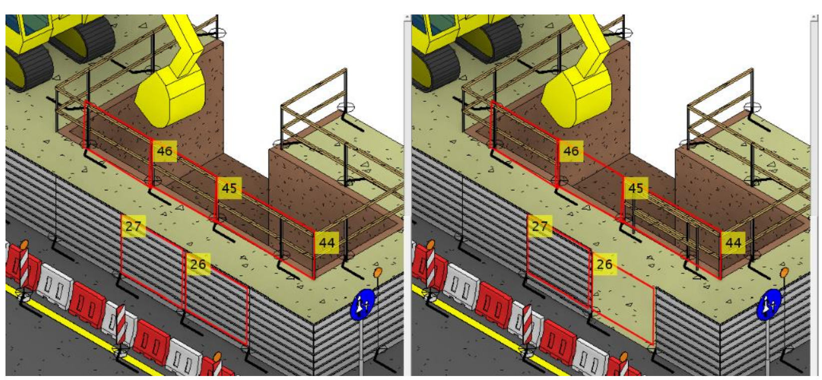


Fig.5: Original and current site images with difference indications

4. Conclusion

The research outlines a framework for job hazard area identification employing a rule-based checking system to detect whether the appropriate safety measures are fully and properly implemented in the construction site. Risks are associated mainly with the absence or incorrect placement of warning signs, fencing, and safety barriers, which could create work accidents and injuries/fatalities. The proposed method integrates an imaging laser scanner that monitors the project status at regular intervals, BIM software for developing an electronic temporary image of the project site, and an algorithm that compares the current temporary image with the original one for automatically checking any possible removal or misplacement of the above safety measures. A Matlab code is used to deploy the hazard identification algorithm at a number of predetermined check areas. If differences between the original and current safety measure placements are detected, which indicate improper removal or deviation from appropriate arrangement, the type and the area of the potential risk for workers' safety and health are indicated by displaying the two images in contrast, with the image frames under interest clearly highlighted. An alert is following raised via e-mail message to project or site manager, specifying the point and type of nonconformity. The alerting process can result in prompt response and appropriate restoration of safety measures, preventing thus accidents and reducing the possibility of undesired consequences to project execution.

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Building Information Models' data for machine learning systems in construction management

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Abstract

Qualitative and quantitative data are important in construction management. However, despite the capabilities of construction informatics, such data and its sources have scarcely been fully and systematically utilized for predictive purposes. Building Information Models (BIM) are such a data source. Within BIM, information structures enabling interoperability and providing utilizable data throughout the various Levels of Development (LODs) of a building – for example, Industry Foundation Classes (IFCs) – can be fully and meaningfully exploited through data mining, and more particularly, via machine learning. In this paper, the capabilities of the information structures found in IFCs to be used as data sources for developing machine learning predictive models, will be examined. In addition, and by conceptually tying such data with constructability, their suitability for predicting – through such machine learning models – the delivery cost and time overheads of a construction project, will be considered.

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Keywords: Building Information Models; construction informatics; data mining; Industry Foundation Classes; machine learning

1. Introduction

Construction management (CM) strives to optimize a project's performance (namely, its delivery time, cost and quality) [1]. A key factor to successful CM is the collection, understanding, and processing of relevant data [2,3]. Within construction informatics (CI) – namely, the interdisciplinary applied field combining construction, information systems and computer science and studying issues related to design, processing, representation, communication and use of construction-specific information in humans and software [4] – methodologies are explored for such meaningful data utilization [5], including data mining, machine learning (ML), and Building Information Models (BIM) – with the latter also serving as data sources [2,3,5]. Data mining is the set of processes that computationally discover and comprehend patterns in datasets, with a combined human-machine effort [2,6]. ML, used in state-of-the-art data mining [2,7], is the exploration of algorithms that enable computing systems to "learn" and make data-driven predictions by building a model from a sample dataset [7]. While the discretization of ML varies in the relevant literature, it is largely categorized into supervised (SML), unsupervised (UML), and hybrid (HML). SML utilizes datasets featuring a known structure and labelled instances to train and validate suitable algorithms, assuming that the reasoning of the application domain is known [8,9]. UML deals with datasets having unlabelled instances and hidden patterns [7]; after presented with some data, the UML system has to develop relational models from that data "on its own" [9]. HML mixes two or more approaches and can include semi-supervised and reinforced learning [9]. Finally, BIM are sets of interacting

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policies, processes and technologies for digital building design and lifecycle project data management [2,3]. BIM can, in principle, contain numerous interoperable information structures with ordered utilizable data, applicable throughout the lifecycle and the various Levels of Development (LODs) of a building project – for example, Industry Foundation Classes (IFCs), aecXML, and change logs [10].

Qualitative (e.g. lessons-learned databases) and quantitative (e.g. cost and time overheads) data, found either in BIM or elsewhere, can be utilized within CM [2,3,4,11]. However, despite the capabilities of CI, this has scarcely been done systematically [2], but rather in a fragmented informatory manner [2], or for more narrow applications [2,12]. Empirical knowledge is still the main driving force of construction management, even when aided by construction informatics tools like BIM [2,13] and ML [3,14]. But while experience is essential, a more holistic CI-aided utilization of existing data could enhance construction managers' decision-making and action-taking regarding project performance [14]. Data found within BIM, and especially in IFCs, can aid in such an effort [10], and ML can help in exploiting such data [2,13].

In this paper, the capabilities of BIM as data sources for ML models within CM, and their suitability for predicting the delivery cost and time overheads of a building, will be examined. In the second section, a literature review on notable construction-related ML uses, and the absence of BIM data utilization for project performance prediction, will be showcased. In the third section, data structures within IFCs will be highlighted and tied with constructability in a conceptual framework for ML modelling. In the fourth section, conclusions regarding the current effort are drawn.

2. Machine learning modelling within the construction sector

ML is central within the digital transformation of research and the industry [15], and indeed within construction [16]. In the latter, the earliest attempts on ML implementation generally refer to the computer-aided acquisition and processing of design- and construction-related expert knowledge [17,18]. Since then, SML systems have been developed to support bidding processes, such as in the analysis of contractual texts for relevant requirements [19], and building code compliance checking [20,21]. SML inference models have been used to estimate the completion time of whole projects or individual components [22,23]. In [24], SML algorithms were tested for developing a building energy consumption predicting system, whereas in [25] the energy consumption of office buildings was investigated via a hybrid approach. SML for image recognition has been proposed and tested for construction surveillance issues (such as concrete quality, on-site worker movement, and construction injury prediction) [12], analysis of pictures of roofs to prevent occupational accidents [26], web image processing to detect road surface cracks [27], and automated on-site detection of workers and heavy equipment [28]. Apart from the system in [12], SML has also been deployed to identify root causes of occupational accidents [29], and has been coupled with the cross-industry standard process for data mining (CRISP-DM) framework to develop on-site safety leading indicators [30]. Moreover, SML has been intertwined with plot analysis to assess key project performance indicators [31], and with deep learning (namely, gradient-based optimization to adjust parameters throughout a multilayered network, based on errors at its output [32]) for the electroencephalography-based recognition of construction workers' stress while performing on-site tasks [33] and the detection of non-certified work on-site [34]. In a SML deployment touching on the Internet of Things (IoT), data was collected from sensors in an operating building, and then used to reduce the occurrence of design errors [35]. Construction productivity has also been assessed with SML [36], as well as buildability during the project design phase [37]. SML has even been tested to predict construction costs [38] and the attributes of structural materials [39]. There are far fewer notable examples of UML deployment, such as in aiding design integration by implementing construction knowledge and experience [40], and deriving construction project risk sources [41]. Moreover, HML implementation has been relatively scarce (e.g. [25]). There have been mixed systems, utilizing SML and UML either complementarily or interchangeably, such as cooling control systems in office buildings [42], and the use of the results of [41] in a SML system appraising the constructability of technical projects [43,44].

The study and ML-induced utilization of BIM data has been given smaller attention, even less so for predicting project performance (e.g. in terms of time and cost) [45]. Among the few related efforts, the following are the most notable:

- Data pre-processing in: (a) the development of as-built BIM models (e.g. through the classification of apartment rooms [46], heritage buildings [47], sensor-independent point cloud data as part of the scan-to-BIM process [48], and through masonry wall defect surveying [49]), and (b) the textual classification of maintenance work orders for the integration of BIM with facilities management [50].
- Leveraging the capabilities of BIM for quality control and code compliance [51,52].
- Knowledge discovery within BIM, as part of cognitive assistance frameworks [53,54,55,56,57,58].

The efforts especially mentioned in the last bullet present the most advanced cases of processing and exploiting BIM data; however, they mainly focus on the improvement and back-propagation of BIM models themselves. In [53,57,58] this approach is indeed coupled with the development of predictive systems, but in distinct contexts (e.g. energy performance prediction [55]), and not for assessing major indicators of project performance (time, cost and quality).

3. Data in IFCs and constructability for machine learning predicting indicators of project performance

The Industry Foundation Classes (IFCs), were designed to provide a universal basis for information sharing over the whole building lifecycle [10,47], as de facto standards for representing BIM. IFCs define entity-relationship data models, encompassing entities organized into object-based inheritance hierarchies [10,47]. IFCs are considered comprehensive and support a wide variety of buildings objects, such as IfcWall, IfcBeam, IfcWindow and IfcRoof, together with the option of interconnecting an unlimited set of properties and quantities to each object. All base objects have globally unique identifiers (GUID) that can be made persistent for the project – thus allowing multiple IFCs to merge deterministically, while keeping their data integrity without human intervention. Using the IfcRelation feature, any object can also relate to other objects, making it possible to form constraints and relations between building parts. A major difference between IFC and general 3D-file formats is the representation of space – every instance of an IFC-object must belong to a spatial context. Special space-enclosing structures are the sites (IfcSite), buildings (IfcBuilding), storeys (IfcBuildingStorey), and rooms (IfcSpace). In addition, IFCs have a, less used, support for processes and resources. IfcProcess is the base class for processes (e.g. tasks and events) and may be assigned to products to indicate the output of performed work. IfcResource is the base class for resources (e.g. materials, labor, equipment) and their associated cost- and time-related constraints, and may be assigned to processes to indicate tasks performed on behalf of a resource.

Data ordered with IFC can be reviewed and studied with BIM model checking software tools, such as Solibri. Then, it can be suitably mined manually, with semantic and/or latent techniques ([53,54,55,56,57,58]), or with dedicated data parsers [59], and exported into file formats as input for ML suites; examples of such formats are .arff files for the Waikato Environment for Knowledge Analysis (WEKA), or structured .csv files to be incorporated in ML libraries of the Surprise Scikit, a Python-powered scientific toolkit for recommender systems. But for this data to be translated into meaningful independent input variables, and then connected with meaningful dependent output variables as part of a ML modelling (and especially SML) addressing the research gap mentioned in the previous section (namely, the absence of BIM data utilization for the prediction of a building project’s performance, and especially its delivery cost and time overheads), it needs to be incorporated in a suitable theoretical and conceptual framework. One such framework is constructability, namely the optimal use of construction knowledge and experience in planning, design, procurement, and field operations to achieve the project objectives of time, cost and quality [43]. Situations where construction knowledge and experience are not implemented properly, resulting in the widening of the gap between the “as-designed” and “as-built” project states and ultimately in sub-optimal project objectives, are defined as constructability problems [43]. In the data mined from IFC-ordered BIM (e.g. components types and system types, manufactured products), the elements mainly translated into constructability problems are geometric and dimensional discrepancies, detected design clashes, construction site spatial and schedule clashes, timeframe conflicts, logistics and material quantity problems, and the number of reworks. By exploiting (a) the direct connection of constructability to the overall project objectives rather than narrow applications, (b) its affiliation with construction knowledge and experience implementation, and (c) the capabilities of CI technologies to extract and process data that can be interpreted as constructability problems, a novel predicting system that will holistically extend the perception and enhance the decision-making and action-taking of construction managers, can be formulated. Derived from the aforementioned insights, an early conceptual framework of such a formulation can be delineated in the following steps:

Step 1. Data collection. For a large number of building projects, BIM data displaying the as-designed and (whenever applicable) the as-built states will be sought; this data may be (a) quantitative, including components and system types, manufactured products, geometric and dimensional discrepancies, and design clashes; and (b) qualitative, such as descriptions of spatial and schedule clashes, timeframe conflicts, logistics and material quantity problems, and the number of reworks. This data will reveal constructability problems (i.e. the input variables of the ML system), and will be extracted and exported into suitable file formats. Then, for the same projects, documented data on the corresponding delivery cost and time overheads (i.e. the output variables) will be sought via expert input.

Step 2. Variable formulation. Independent variables: Depending on the form of the constructability problems-related data, meaningful independent variables (e.g. "Number of reworks") measured through the values of the collected data will be produced through UML techniques such as vector quantization and linguistic clustering [43,44], or qualitative techniques relying on expert input (e.g. brainstorming sessions). Dependent variables: Depending on whether the building delivery time and cost data is discrete or continuous (e.g. whether a building's completion delay is expressed in months or with yes/no statements), the dependent variables (namely, "Overheads on the intended cost" and "Delay in the time of completion"), will be formulated to be used for classification or regression, respectively. This will also lead to the choice of the relative SML scheme in Step 3.

Step 3. System formulation. The choice of the SML scheme to be trained and validated depends on the data form and amount, and the variables' type and number. Multiple experiments will be conducted within a suitable ML platform, with numerous SML schemes. In the current research and practice, support vector machines (SVM) and support vector regression (SVR) are, respectively, the most widely used schemes for binomial classification or regression, and variations of the random forest scheme are the most widely used for the multinomial cases [9,43].

Auxiliary mathematical, methodological and software tools may be utilized within Steps 1-3, e.g.: (a) non-negative matrix factorization for data normalization and pre-processing (Steps 1-2), (b) multi-input Analytical Hierarchy Process (AHP), for variable labelling (Step 2), (b) the "kernel trick", to aid in the non-linear function SVM or SVR (Step 3), (d) n-fold cross-validation, for the simultaneous SML training and validation (Step 3), (e) the WEKA platform (Step 3), (f) Surprise Scikit (Steps 2-3), and (g) the programming language Python (Steps 2-3).

Step 4. Integration of results. The ML system can be integrated as a working prototype within BIMs of new buildings, for the verification of its predicting results – namely, whether a new building will display delivery cost and time overheads, in relation to the detected constructability problems affecting it. This will take place through suitable programming routines and/or graphical user interfaces (such as PyQt, featured in the Anaconda platform).

Such a novel methodological framework and subsequent modelling can furtherly strengthen the placement of ML within CI (and particularly, BIM), for the benefit of construction managers and related disciplines.

4. Conclusions

IFC-ordered data contained in BIMs, are a rich and utilizable source for optimizing construction management. They can be understood and processed through the lens of constructability, extracted via the relative tools and methodologies, coupled with expert input, and used for training and validating machine learning systems predicting the delivery cost and time overheads of a building. This paper offers the first theoretical and conceptual insights of such a process. Future work will hopefully encompass the actual realization of the conceptual framework through data mining and expert processes, as well as the related ML algorithm deployment and experimentation for the derivation of the final results.

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Combining BIM and Last Planner on construction sites: an investigation of the related challenges

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Abstract

The construction industry is facing a gradual but important transformation towards more productivity and collaboration. In this framework, two major approaches are often cited in the literature as having the potential to improve the practices in the industry: Building Information Modeling (BIM) and Lean Construction. Several scientific studies have demonstrated the synergy of these two approaches and very recent research has reported positive results from the use of software applications as support for their implementation on construction sites. However, the stakes of such integration have been very little studied. This article presents the results of a research project conducted within a general contractor firm that decided to implement BIM and Last Planner System (LPS) on its construction sites. The research uses a four-stage action research approach, including the characterization of the research issue, the establishment of an action plan, its implementation and its evaluation.
Compared to recent related studies, the research is less enthusiastic. While it highlights the need for new tools to improve production planning and control, it also points to a strong resistance to change by practitioners at the site. They emphasize the necessity for adequate pre-service training and the need for new resources that can work full-time on the ongoing training of site teams. In addition, some limitations of the tool lead workers to believe that it can quickly become a factor that slows down their daily work rather than improving it.

Keywords: Building Information Modeling; Last Planner System; Construction site.

1. Introduction

The construction industry is generally considered to be an underperforming industry, compared to other manufacturing industries such as aerospace and automotive [1,2]. This lack of performance is reflected in particular by low productivity and frequent overruns of costs and delays [3–5]. Yet, in recent years, the growing adoption of new technological approaches seems to have the potential to change the game [6]. Among these approaches, Building Information Modeling (BIM) occupies an important place [7]. The early years of the BIM approach focused on the development of technological solutions, for example to solve important issues such as interoperability. But rather quickly, it became clear that the added value of such an approach should reside, not only in the arrival of new technologies, but also and above all in improving the dynamics of collaboration, the integration of the supply chain and the elimination of waste. In this context, several research projects have highlighted the necessary complementarity between BIM and Lean approaches [8,9]. The synergy between the two approaches has been

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widely discussed in the literature and the added value of such a combination has been demonstrated [10–13]. But very little work has been devoted to the issues related to the combined use of these two approaches, which, even if they are recognized as complementary, each require a particular methodology and important means to implement.

This article presents the results of a research project conducted with a general contractor firm that decided to implement BIM and Last Planner System (LPS) on its construction sites. It aims at exploring the main challenges to overcome in order to successfully implement LSP-BIM software. The rest of the article is organized in four main sections. The first section presents a literature review whose purpose is to define the main concepts to understand the problem, and to present the state of the art on the question. The second section presents the research methodology. The third part presents the main results, which are discussed next in the fourth section.

2. Related works

2.1. Definitions and main concepts

The success of Lean principles and the perceived benefits of using it in the manufacturing industry have prompted construction stakeholders to adopt these principles [14]. According to Koskela et al. [15], Lean Construction is a way of studying the production system by minimizing waste of materials, time and effort in order to generate maximum added value. Among the various Lean Construction techniques, LPS is one of the most popular methods of production planning and control [16]. The LPS was developed to improve the performance of construction projects by increasing the reliability of schedules and workflow [17]. It is also used to reduce variability and uncertainty in construction [18]. According to Ballard and Howell [19] the planning process of the Last Planner system is a procedure for creating a Master Schedule, a Reversed Phase Scheduling, a Lookahead Schedule, and a Weekly Work Plan, using Lean Construction planning techniques.

Building Information Modeling (BIM) consists in the use of “a multidisciplinary object-oriented 3D model of the constructed facility to improve and to document its design and to simulate different aspects of its construction or its operation” [20]. Thus, it focuses on the development, the use and the transfer of digital information models of a construction project to improve its design, construction and operation [21]. BIM becomes essential for the realization of construction projects and its deployment offers both benefits and challenges in its implementation [22]. It is increasingly required in the execution of projects and for many clients it becomes a requirement to be fulfilled for the grant of the project. Its importance and effectiveness have been proven through several projects [7]. Additional information can be added to the three-dimensional model(s) for analyses and simulation purposes. In this context, it is commonly agreed that 4D models are created by linking scheduling information to the 3D model in order to simulate the process of construction over time [23]. 5D BIM models are prepared for cost management purposes [24]. It is more and more accepted that the sixth and the seventh dimensions are related to energy analysis and assets management purposes, but it is important to note that beyond the fifth dimension (i.e. cost), there is no consensus in the literature about what each dimension represents.

2.2. BIM and LPS association in the literature

In 2010, Sacks et al. [11] conducted an analysis of the interactions between BIM and Lean approaches. They noticed that “a synergy exists which, if properly understood in theoretical terms, can be exploited to improve construction processes beyond the degree to which it might be improved by application of either of these paradigms independently”. They then proposed a juxtaposition of the Lean Construction principles and the BIM functionalities, and factually identified 56 interactions [11]. In 2014, Khan and Tzortzopoulos [25] proposed a discussion on how the association of BIM and LPS can affect the design workflow. The discussion, based on two building design projects, used the interaction matrix developed by Sacks et al. [11] and showed that such an association “can improve workflow in building projects through features that reduce waste”. Indeed, as demonstrated by Seppänen et al. [26], to be fully successful, the BIM adoption needs to be associated with a lean managerial approach like LPS to control. Otherwise, the implementation “can lead to inefficiencies even when the technological approach is effective” [25].

The case study presented by Clemente and Cachadinha [13] identified a number of contributions of BIM to the materialization of the principles of Lean, based on the fact that the BIM methodology has parallel principles with most of the Lean Construction principles. According to Clemente and Cachadinha [13], the BIM model can add a needed visual dimension to the project. This visual dimension can be aligned to all the information available and the BIM features can be exported, so “the works were easily controlled and the facility management improved. This also enabled the implementation of a LPS planning approach for daily activities planning” [13]. However, some limitations and constraints have been identified, including the initial cost, the know-how and the fact that BIM is a time-consuming approach.

More and more commercial software are being proposed, aiming at combining BIM and Lean principles, using mobile technologies. These tools include *BIM 360 Plan, LeanKit, VisiLean, TouchPlan*, etc. *BIM 360 Plan* is a collaborative 'Look Ahead Planning' tool. The master schedule can come from traditional planning tools (MS Project or Primavera). *Leankit* uses a virtual Kanban board, to enable the creation of a master schedule with the participation of the whole construction team, but does not offer visualization of the 3D model. *VisiLean* is a production management system specifically designed for planning and production control. It supports the Last Planner system workflow, including detailed constraint analysis and assignment of resources to tasks. The master schedule and the 3D model are imported into the software. It allows simultaneous visualization of the Gantt and the 3D model for 4D simulation purposes. *TouchPlan* uses a virtual table integrated in the software, to enable the creation of a master schedule. It is also possible to import a master schedule from traditional planning software such as *MS Project* or *Primavera*. However, it does not display the 3D model. Very few research works [29–31] have been dedicated to the evaluation of Lean-BIM software, especially from the perspective of the practitioners.

3. Research approach

Action research is considered as a research method that requires contact with the field and the reality. The purpose of this approach is to identify needs or problems, before establishing a strategy to achieve change objectives in response to observed problems [32]. The action research follows the four main steps: the characterization of the research issue, the establishment of an action plan, its implementation and its evaluation.

The analysis of existing processes used by the industrial partner highlighted some gaps to cover by the implementation of a new technological tool that combines LPS and BIM. To understand the context and the needs, an analysis of the planning and production practices as well as interviews with the involved actors (Project Manager, Superintendent, Planner, and Assistant Project Manager) was necessary. The action plan established as part of this research consists of the following steps: Choosing a solution, defining a scenario, choosing a pilot project, implementing the solution and gathering feedback from project stakeholders. The choice of the solution is made based on selection criteria coming from a synthesis of the literature, including the BIM features, LPS features, collaboration and interoperability features, usability, and accessibility. The scenario adopted consists of a preliminary step of training the participants and organizing an indoor simulation on the operation and use of the software, and to define with the participants an action plan for the use of the solution on the construction site. A pilot project was selected to test the software, relating to the construction of a sports centre and whose structure consists of steel and reinforced concrete elements. The project is realized in turnkey and Fast Track modes. The practitioners' feedbacks were collected through semi-directive interviews.

4. Main results

4.1. Choosing new tools to improve production planning and control

The industrial partner is facing problems related to the limitations of traditional methods of planning and controlling production. The current planning method is traditional (Push Planning) and its practice generates the difficulties such as the delay in the delivery of the works, the waste, and a decrease in productivity. The master schedule is designed in general without much contribution from the specialized contractors. The visualization of the schedule in BIM 4D is not yet adopted by the industrial partner. Certainly, there are important advances in terms of information sharing through the *Procore* project management platform, since all the reports and the drawings are accessible through this platform. The need for new tools integrating BIM and LPS comes from the desire of the industrial partner to improve it production planning and control. But such integration should not be limited to software tools alone, but should take into account the need to update current processes, in order to create a propitious context for the successful implementation of the software on construction sites.

Following the analysis of the planning software integrating LPS and BIM, and according to the identified selection criteria, the two selected software are *BIM 360 Plan* and *VisiLean*. Admittedly, the two programs are similar and make it possible to perform collaborative planning and production control with different approaches. However, *BIM 360 Plan* looks a lot more at collaborative planning while *VisiLean* has an additional function which offers a visualization of the elements of the project through the 3D model. It has been decided to test and to evaluate *BIM 360 Plan* for production planning and *VisiLean* for production control. In this logic, the planning process is divided into three phases: preliminary planning, planning integrating the LPS, and the use of the *BIM 360 Plan*. The preliminary planning is done in collaboration with the construction team and the planner. They use the drawings and the 3D model to generate a preliminary schedule. The schedule integrating the LPS is done in collaboration with the construction team, the planner and all the specialized contractors. They refer to the preliminary schedule, the 3D drawings and models to produce a schedule according to the LPS approach. The use of *BIM 360 Plan* converts the schedule defined according to the LPS approach into 'Milestone Breakdown Structure', and proposes an electronic version of the detailed schedule, and the lookahead Schedule. The 'Weekly Work Plan' and the 'Daily Work Plan / Coordination' are generated by the software. The construction team must ensure that all specialized contractors have access to the software so that they can plan to perform the tasks to which they are committed.

Regarding the production control using *VisiLean*, a working process has also been proposed. Before starting the execution of the tasks, the specialized contractors must carry out a constraint analysis 'Constraint Removal', this allows them to make the task ready to be executed (Task Make Ready). The software calculates the weekly Percent Plan Complete (PPC) for each specialized contractor. The construction team having access to the software can consult the progress of the work of each specialized contractor, and ensure by a physical verification in the field if the work is compliant or does not comply. The PPC produced by each specialized contractor, in addition to physical verification, can help the validation of the payment request of the specialized contractors. The Project Control Manager also has access to the software. This allows him not only to monitor the progress of the work of the specialized contractors, but also to know the overall progress of the work of the general contractor (by consulting the PPC to date). An instant notification system informs all project stakeholders of changes. The control manager and the management team are informed daily of the status of the project. The verification and the validation of the payment requests of the specialized contractors and the general contractor are made easy. For this preliminary case study on issues related to the implementation, we limited the research to the specialized contractors and the general contractor.

4.2. The main challenges

The study showed a contradiction of point of view between the top management and the site team. The top management manifests the need to innovate and supports the idea of implementing the software. For the top management, such an implementation can be useful not only to optimize the planning process, but also to enable a variety of new usages. For example, using the software can help in "exploring the capability to leverage the PPC report data to facilitate the payment of subcontractors", said the project director at an introductory meeting. Moreover, the top management was keen to reduce delays when performing the site work. "Can an alert be triggered when an activity is late compared to its due date?" asked the project director. However, the construction team has an opinion contrary to that of top management. It finds that the adoption of this software means an additional constraint. The construction team finds it difficult, if not impossible, to get the cooperation of all the specialized contractors as the assistant project manager testifies: "It will be impossible to use in the field because all the employees are busy and specialized contractors will not be able to collaborate". “Superintendents and representatives of subcontractors will have a hard time accepting to use it because the software increases the volume of work", he adds. Throughout the participant interviews, participants expressed doubt about the operation and effectiveness of this new software.

The site team showed strong opposition to the implementation of the tool. For 70% of participants, the hesitation and the doubt are justified by the lack of knowledge and experience on the software. For 30% of participants, reluctance to adopt a new, little-known approach creates resistance to change. They find that it is risky to rely entirely on technology. "When the system does not work after an internet interruption or technical failure, it delays our work and we are wasting time", the superintendent stated.

The lack of knowledge is frequently mentioned in interviews. Eight out of ten participants (80%) do not know the LPS, however the 10 respondents say they know BIM. This lack of knowledge is justified by the fact that the LPS is a new concept for many construction companies. However, encouraging feedbacks have been received from the planner: "We would like to adopt the LPS if it is an approach that will simplify our planning", he says. For a successful adoption of the LPS, it is important to train the workers and to show them the added value of this approach. The need for training was raised by each of the interview participants. It is important to set up a continuing education program for software users, in both LPS and BIM. The testimonials gathered are of the same opinion as that of the project manager. "I think that we must train workers to hope to successfully implement the software combining LPS and BIM, and require its use in contractual clauses", he says. The Superintendent draws on his past experience with implementing BIM to emphasize the importance of worker training. "BIM is a very good tool, but workers do not know how to use it", he concludes.

Throughout the interviews, participants expressed doubt about the operation and effectiveness of this new software. For 70% of participants (seven out of 10), hesitation and doubt are justified by the lack of knowledge and experience on the software. For 30% of participants (three out of ten), reluctance to adopt a new, and little-known approach creates resistance to change. They find that it is risky to rely entirely on TM, as the Superintendent testifies, "When the system does not work after an internet interruption or technical failure, it delays our work and we are wasting time. Having a full-time person in the field for technical assistance and ongoing training of software users can simplify the software adoption, and can motivate and encourage workers to use the software well. The superintendent's testimony supports the need to have a champion assigned to the project "This is a good opportunity, but it will be difficult to implement if a resource responsible for the tool is not recruited to conduct the implementation ". The project manager is of the same opinion. "Not having a person dedicated to the management of the documentation makes the work of the project manager quite painful when searching for documents. [...] We must also recruit a person in full time who will take care of the daily training of users and the use of LPS and BIM software throughout the project", he says.

5. Conclusion and future work

The research presented in this paper aims at exploring the main challenges to overcome in order to successfully implement LSP-BIM software. It highlights the need for new tools to improve production planning and control, but also points to a strong resistance to change by practitioners at the site. They emphasize the necessity for adequate pre-service training and the need for new resources that can work full-time on the ongoing training of site teams. In addition, some limitations of the tool lead workers to believe that it can quickly become a factor that slows down their daily work rather than improving it. Future works will focus on how to optimize the continuum of information between design team and the construction site, in order to fully benefit from the capabilities offered by BIM models.

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Development of an AR system for the advancement of the tasks in the construction sites

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Abstract

In this paper, we developed an AR (Augmented Reality) application for productivity improvement in the construction sites. We developed this system for upgrading the ancient methods of construction by using the AR Technology. The main concept of this system is to use the AR technology for visualizing the completed form of the buildings, reforming the "construction management" and improving the productivity on the construction sites. This system can be used for the "presentation of the completed models" for early decision of the task to be performed, "safety work confirmation" for eliminating and reducing the dangerous tasks, "visualization of completed model before the completion of the buildings" for eradication of serious mistakes on quality of the buildings to be build. Generally, the AR system is used along with various types of head worn devices like Head mount displays or Google glass, but they are not realistic for the construction workers or in the construction sites. Our application works on iPad® ® and tablets which is easy to use and is a realistic form of using AR in the construction sites. Our application is developed in such a way that, the AR model generated from the BIM (Building Information Modeling), projected on 1:1 scale in a real space is continuously displayed in a smart device following the movement of the person holding the tablet. As a person moves holding the tablet, the position and orientation of the tablet is tracked, and the model follows the tablet. The developed system is experimented on the building construction sites in Japan. The experiments were conducted by developing the AR models from the BIM model of the various areas of the architectural construction sites. The experimental results reflect the effectivity of our AR system for increasing the productivity of the construction sites.

Keywords: Architecture; Augmented Reality; Building Information Modeling (BIM); Construction;

1. Introduction

Augmented Reality (AR) is a Computer vision system that gives a view of the real world where the elements are superimposed by computer generated files as graphics, sounds, videos or digital information. AR was first developed in 1968 by Ivan Sutherland at Harvard, where the users were able to experience the computer graphics that made them feel being in the alternate reality. Been around for numerous decades, various developments have been made in the field of AR. The implementation of AR in the medical and various other fields are spreading as a part of business innovation but AR technologies were not applied on construction sites due to the tracking and alignment problems in the construction sites, instead they were used at the office for simulation or collaboration during the design phase of a project.

In the recent years, a huge development in the field of AR technology have been made, which shows the possibilities of applying the AR in the field of construction sites. The construction industry is dependent on visual imaging solutions for achieving the functions related and performance related information. One of the leading

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innovations for visual imaging in the field of ICT Augmented Reality (AR), which brings virtual objects in the same axis with real world and enables monitoring the virtual objects together with the real world where they are relayed (1). Shin and Dunston (2) states that the AR technology provides various advantages through visualization and Simulation of the construction industry. As an example, allowing the observer to interact with both the actual and the virtual objects and monitor the construction progress by comparing the as planned and as built status of the project (2). In the past research, Wang and Dunston mentioned that it is very impracticable to train a heavy construction equipment operator in a real condition, so they developed an AR based heavy equipment operator training system called ARTS (3). A 4-dimensional AR model was developed for automating the construction progress monitoring and data collection, processing and communication in the construction phase of the project (4). Various web based augmented panoramic environment are developed for the documentation of the construction progress (5).

The common problems like, delay and misrecognition of the fixed things, critical quality accident of the frame (pile, rebar etc.), mistakes in finishing materials, misplacing equipment's, inadequate provisional equipment's, lack of building maintenance information and others still occur in the construction sites. These problems are time consuming as well expensive. To overcome with these problems one by one, we think of some ideas on using the AR in the field of constructions to bring the advancement in the ancient tasks performed in the construction sites. We develop a concept of mobile AR application, aimed to visualize the completed form of the models in the construction sites. Since, we have developed an AR application that can be used on the iPad® s on the construction sites. In this paper, we will introduce about this application and its real implementation in the construction fields by on-site employees.

Our application is designed to be used in an iPad® by connecting with the structure sensor. The two fiducial markers are installed at the local reference point in the sites for detecting the position of the model to be displayed in the iPad® screen. When the two fiducial markers are detected by the structure sensors, the AR model generated form the BIM (Building Information Modelling), projected on 1:1 scale in a real space is continuously displayed in an iPad® following the movement of the person holding the iPad®. This application was experimented and tested in various construction sites in Japan for validating the effectiveness of our AR application.

2. Related Works

The mobile AR application was first presented in the Columbia University Campus for viewing the information around the campus area, with a PC and Head Mount Display (HMD) (6). After some years, the marker-based AR system (7) was introduced. The system was then developed by combining the hybrid computer vision and sensor-based tracking for mobile outdoor applications (8). AR tracking these days are available for mobile phones and tablets being based on the GPS and compass sensors or IMU device. An accurate 3D tracking technology in the construction sites was introduced by utilizing the 3D points clouds generated from the site photos (9). The tracking system developed by using the 3D point clouds were then made able to work on live videos (10).

Due to the limitations of the GPS, the mobile AR application are being used widely in the outdoor environment. In case of the indoor environment, the localization of the AR points or the device is a challenging job. A mobile AR application presented few years ago combine various computer vision tools, 3D reconstructions and sensors to provide reliable tracking (11), This system integrate the BIM data in their system. Our application is somewhat similar with these system in the current perspective. The Info SPOT system was an approach for mobile AR maintenance that utilized BIM for facility management based on predefined natural markers (12). Various related works have been done, but the difference to our system is, we are using the extended AR tracking system and a location-based AR model visualization process. We are using the structure device for calculating the movement and the position of the device, the fiducial markers are used to localize the point for displaying the AR model.

3. AR Application Prototype

3.1. Overview

The tasks performed in the construction sites are generally done by using the traditional methods and are the best way for getting the proper output, but it depends on the construction workers and their experiences. In the coming future, the Japanese Constructions will lack a lot of manpower to work in the sites because of the decreasing population in Japan, the old and experienced people will be retired, and the young peoples are not interested to work in the construction sites. Apart from this, a lot of problems related to the tasks in the construction sites usually occurs in a huge amount almost every day. The problems can be classified as the "delay and misunderstanding in fixing and decision making", "Serious quality accident of the frame (Pile, rebar etc.)", "facility positioning error", "mistake in the finishing materials", "Inadequate temporary facilities", "lack of building maintenance information" and so on. To overcome with these problems, we developed an AR application for the advancement of the tasks in the construction sites. The current application is designed and developed to use in the construction sites by using the smart devices such as iPad®, iPhone®, tablets® etc. The main concept of our current application is to visualize the completed form of the BIM models in the construction sites using the AR technology.

3.2. Structure of the Proposed algorithm

The structure of our proposed algorithm is shown in figure 1. We have divided the structure of our algorithms in two parts, first part is the preprocessing as shown in figure 1(a) and second part is the main process of the algorithm as shown in figure 1 (b). In the pre-processing of our proposed algorithm, we work on developing the AR models from the BIM model and fixing the positional relationship of the two AR marker points. We have used the Vuforia™ ™ (13) for fixing the positional relationship of the two AR marker points and save them in the device. The positional relationship of the two AR marker points will be effective for detecting the position of the smart device and continuous display of the AR model with high accuracy in the real construction sites.

In the main process of our proposed algorithm, we attach an external structure sensor (14) with the smart device. As the application is turned on, the structure sensor attached with the iPad® is also turned on. When the structure sensor is turned on, AR space is constructed by using the IMU device, gyro sensor, camera image and depth camera image from the device. The two markers are then placed in the local reference point fixed during the pre-processing. The two markers are then detected by using the infrared camera of the structure sensor. Then the system sets the AR space for displaying the AR model based on the co-ordinates of stored AR marker (two points). AR function is then implemented by superimposing the image capturing the real space and the image capturing the AR space, which in results displays the AR model in the iPad® screen with the scale of 1:1. The AR model is displayed continuously even after the loss of the marker. The tracking algorithm of the structure sensor SDK (14) is used for tracking the position of the device and reflects it in the AR space even the device moves or changes its position. The workers can inspect their works in the construction sites in a real time by comparing the real image and the AR transformed BIM model. The pictorial representation of our proposed algorithm is shown in figure 2.

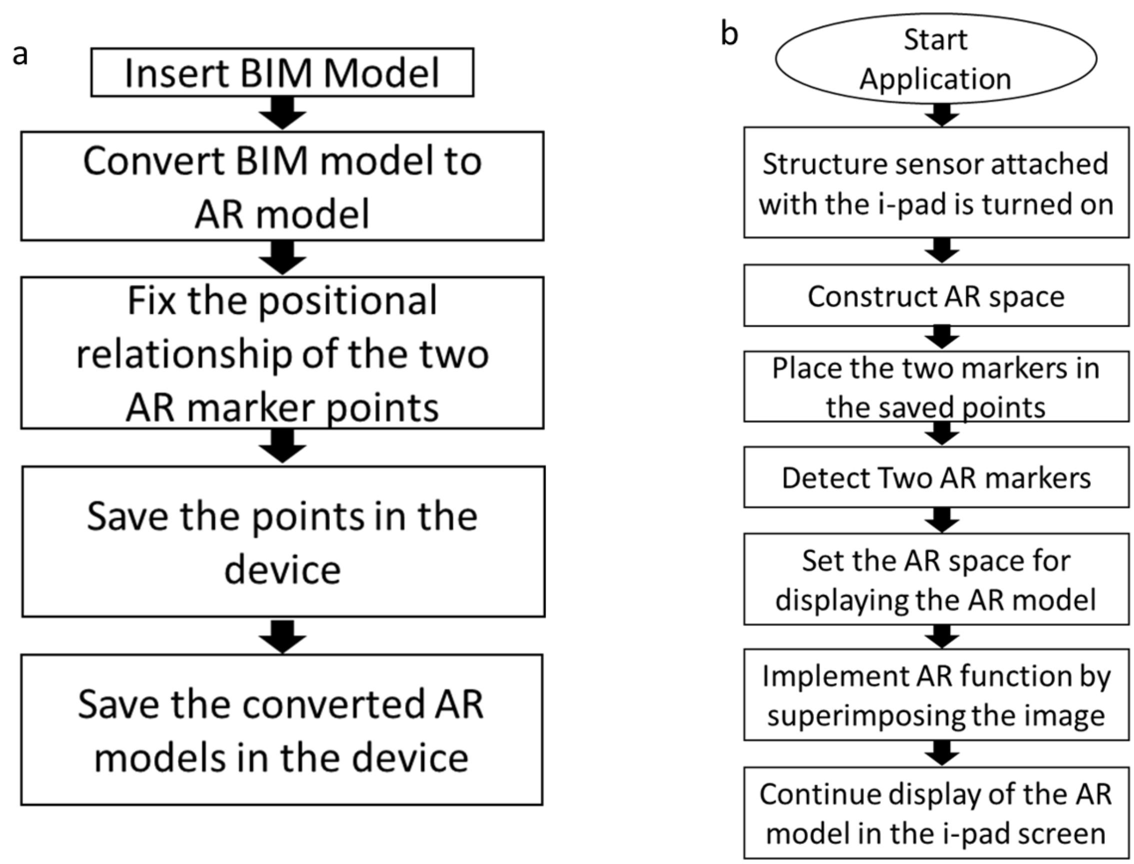

Fig. 1. Proposed algorithm: (a) Pre-processing of the proposed algorithm, (b) Main Process

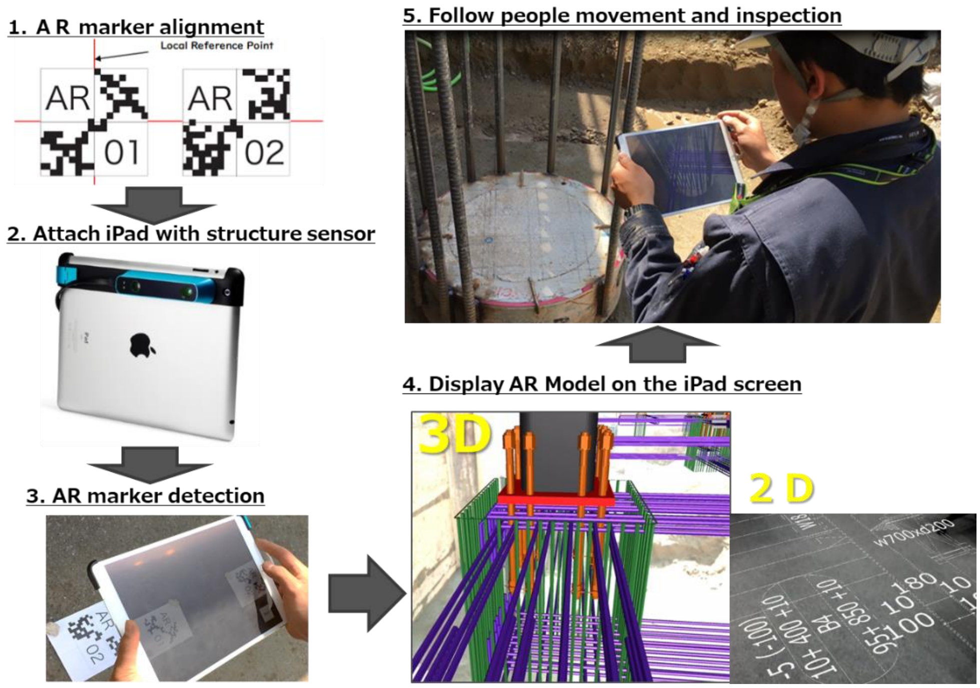

Fig.2. Pictorial representation of our proposed algorithm

3.3. Test case

We choose a 13-storey steel building site for testing our current AR application. The application was applied for the task related to basic reinforcement of the Rebar construction. This task is one of the complicated and complex tasks, where the mistakes and errors related to the foundation beam and foundation pillar occurs very easily. To avoid such mistakes, we developed several AR models from the BIM models for getting the prior confirmation of the completed model in the real sites before starting the tasks or in the middle of the tasks or whenever the workers gets confused. This process is very much effective for reducing the mistakes and errors in the construction sites. In figure 3, image (a) displays the site before applying the AR processing, image (b) displays the 3D image of the site after applying the AR processing and image (c) displays the 2D image of the site after applying AR processing.

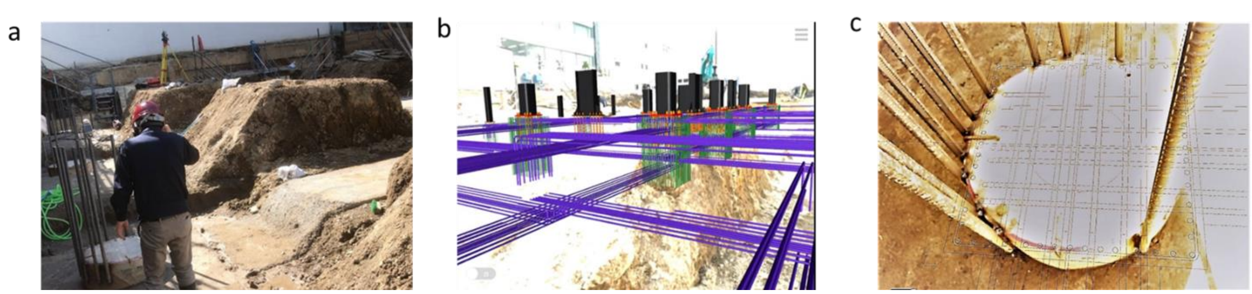

Fig.3 (a). Site before Rebar construction (b). 3D model of Rebar construction (c). 2D model of Rebar construction

3.4. AR Models

In this paper, we focused on the Rebar construction and the Rebar construction is combined of various stages including various parts. In this application we developed and implemented the models related to the Rebar construction. The 3D model of bottom reinforcement, top reinforcement, Pillar and combined model of top and bottom beam reinforcement models were developed for testing in the construction sites. The models are shown in the figure 4. These models are developed for confirming the model before building and eliminate the mistakes and error.

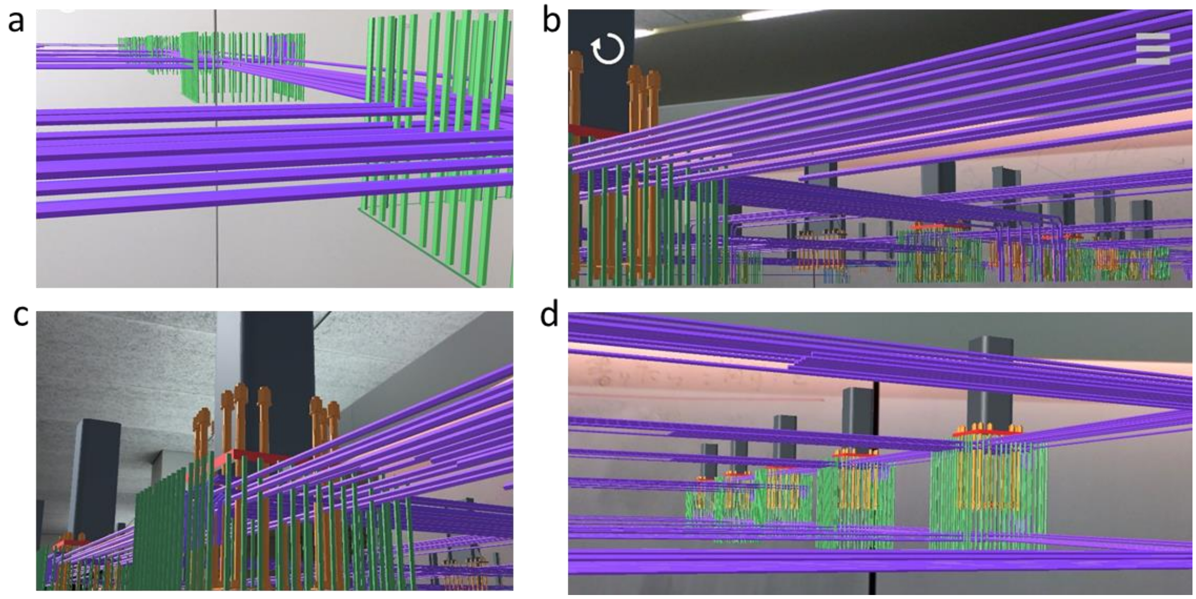

Fig.4 (a). 3D model for bottom reinforcement (b). 3D model for top reinforcement (c). 3D model for pillar (d). 3D model of combined top and bottom reinforcement

4. Testing and Evaluation

We tested our application in the 13-storey steel building construction site of Japan. The test was performed by the construction workers from the main contractor and the workers from the Rebar company for confirming the 3D and 2D models of the Rebar before constructing the basic reinforcement in the site. The application was tested by placing the two AR markers in the site and localized the position of the iPad® by using our application which results in the display of the 3D reinforcement models in the iPad® screen in the scale of 1:1. The model follows the movement of the device and display the model in the proper location calculated from the marker points using the IMU device, Gyro sensor, Real image space and the AR image space.

After testing the application, the site's member evaluated our application as an useful tools in the construction sites, this application can be used in the construction sites as a tool to show the completed model to the customer in the open land, can be used as an educational material because the models are easy to see and understand as they are seen locally in the sites and also can be used for the interference check during the temporary design. Similarly, the Rebar company also evaluated our application as an effective tool for understanding the complex layout model of the basic reinforcement on site in a real time. Our application will be helpful for the prevention of re-arrangement, can be used for checking the joint bar and can be used for checking the reverse strike joint bar for inverted construction method. Due to the problems related to the handshake, IMU device and other hardware tools, the error related to the positioning and localization of the device occurs.

5. Conclusion

In this paper, we have described about the development and the implementation of a prototype AR application to be used in the construction sites. Based on the testing and the evaluation of our application by the construction workers, the application seems to be effective for the construction workers to confirm the complete image of the building models and the materials to be used, the application helped to create the image of the completed model and displayed the model on the local sites with the proper localization of the device in a real time. The iPad® was used as an AR tool for displaying the AR model, is one of the best ideas to be applied in the construction sites in comparison to the head worn devices and the glasses. The use of two markers seemed to be time consuming and needs to be reduced to one marker or marker less. The localization of the device suffered an error in cm precision needs to be improved for using this application in the various construction related tasks. In this paper, we tested with the rebar construction models, but the application can be used for any other models for prior confirmation and visualization of the construction sites locally.

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Discovering the level of BIM Implementation at South African Architecture Schools: A qualitative study.

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Abstract

It is a well-known fact the architecture industry is at the forefront of implementing and using Building Information Modelling (BIM) to conceptualize, develop, resolve and execute buildings. Although it may seem like a new concept, BIM had its foundations set in the 1980's with the disruption being 3D CAD. BIM has significantly been revolutionized beyond the likes of 3D CAD to become a complex system of information. Currently, BIM is still revolutionizing how architects design buildings by intelligently documenting buildings, realistic visualization, error reduction and 3D resolution of construction detailing. However, when and where is BIM implemented to allow architects to maneuver in the complex web of BIM? In recent times, BIM has become a household phrase amongst architecture schools around the world. BIM is fundamentally important in the architectural design and construction courses as it allows students to explore their designs and resolve problems surrounding the resolution of designs, construction of buildings. materiality etc. BIM is a complex system of information and is an ever-changing philosophy that has changed how buildings are conceptualized and executed. As BIM revolutionizes the architecture industry, it is important to grasp the level of implementation and methods of executing the teaching pedagogies in teaching BIM. From various research conducted, it is evident that the architecture industry is at the forefront of BIM implementation, however is this the case at the various schools of architecture? This research focuses on the levels of implementation of BIM at schools of architecture in South Africa. The research makes use of a mixed method approach of both primary and secondary data. The primary method of data collection was executed using a qualitative interview-based approach to unravel the various opportunities and challenges faced at architecture schools in teaching and disseminating BIM knowledge in South Africa. The interview schedule was based on various questions including the current state of implementation, equipment, lecturer's knowledge and importance of an integrated BIM philosophy in courses. The secondary data for this research was collected through an intense literature review that sought to discover the implementation of BIM throughout the world and the opportunities and challenges experienced by other international schools of architecture. Preliminary findings reveal that there is some usage of 2D, and 3D CAD being implemented, however little implementation of BIM methods, processes and pedagogies have been recorded, which prompted the need for research in this key area. This research will be useful to Universities which are currently implementing BIM, the BIM research community, Industry and other stakeholders which wish to contribute to the body of knowledge of Building Information Modelling.

Peer-review under responsibility of the scientific committee of the Creative Construction Conference 2019.

Keywords: BIM; Architecture schools; Pedagogy; South Africa; Industry 4.0

1. Introduction

The introduction of Building Information Modelling into the construction industry has completely revolutionized how Architecture, Engineering and Construction (AEC) professionals carry out their daily tasks. BIM has become a key driver allowing consultants to conceptualize, correct errors, document, estimate and execute projects at a faster rate with better accuracy. Globally, BIM has caught on to all the construction courses more especially the Architecture

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fraternity. The reason for this quick uptake is obvious with the likes of a conceptual design being the opening of a project. Although BIM is a relatively new concept, it has been rapidly introduced into the architectural office. Candidates entering the industry are expected to have a high level of skill with BIM protocols, with that in mind it has been noted that Architectural firms are inclined to hire a candidate with excellent BIM skills more than candidates with great design/construction skills. It then becomes obvious that architectural firms want candidates to produce work from day one. With this disruption, it leads to a key question; where are architectural professionals getting their training from and how effective is it?

With the rapid uptake of BIM in the Architectural Industry, Academic institutions have reacted by implementing the dissemination of BIM knowledge to their students by introducing courses and integration of a BIM component within the design syllabus. It has also been noted that Universities have implemented dedicated BIM labs as part of their infrastructural needs and have hired staff to teach BIM courses. An initial glance at the syllabus of most Universities indicated BIM is being taught at an introductory level and not as a gradual advancement through the years, this becomes problematic as students are equipped with basic skills only. Following on from the syllabus integration, an aspect that has troubled many architecture schools is the hindering of creativity in design due to BIM and understanding of construction detailing with use of BIM. These two key areas form a major part of all architectural syllabi's and it is important to understand the approach towards an integrated BIM philosophy in teaching architecture.

This research intends to discover the level of BIM implementation at Schools of Architecture in South Africa by investigating BIM usage from the perspective of the teachers and students. The research further investigates the pros and cons of BIM in both the design and construction detailing studios. Initial literature reveals that this is an under-researched area and the information produced by this research will be critical to not only understand the usage of BIM at Architectural Schools in South Africa but also to determine what issues are pertinent in disseminating BIM knowledge.

2. Literature Review

In this section the authors examine multiple sources of literature to create a framework to understand the world issues of BIM implementation at schools of architecture. The literature review will be synthesized with the findings of this study and cumulate in recommendations going forward.

2.1. What is Building Information Modelling?

Building Information Modelling (BIM) had its infancy based in the early 1960's with the introduction of 2D CAD and the digital drawing board was born [12]. The digital drawing sector was disrupted even further by the introduction of 3D CAD in the early 1980's and became the successor to 2D CAD [19]. BIM became a workflow to capture rich information such as size, information, geometry, materials etc. whereas AutoCAD only had simple line data [13].

BIM culminates information into a complex 3D model or composite model which allows consultants, contractors and fabricators the opportunity to collaborate within a single database with various data sets for mutual benefit [4]. Similarly, Eastman et al [10] states; BIM fosters a re-think of how the construction industry consultants think and execute buildings in many senses, i.e.; Analysis of various concepts early in the design stage, Analysis of the BIM Model in terms of structure, energy, planning, cost implications, Team collaboration both within the discipline and cross discipline, construction detailing and execution on site, fabrication of various building components and facility management. Sabongi [18] goes on further to elucidate that due to an information- rich data base which is parametric in nature, all aspects of a building can be characterized, analyzed and executed. Azhar [6] states that even though a BIM model is rich in data, it must be accurately constructed digitally for it to hold important information for physical construction. It is of vital importance to understand that BIM is not only a modelling software for visualization but a model that holds deep information of an entire project across disciplines, however are architects implementing the strategies of a BIM system to its full potential on their projects? If so, how are they doing it? In the next section the authors investigate using literature to understand how architects are implementing BIM at their practices.

2.2. BIM education in Architecture Schools

In this section the authors investigate various topics including but not limited to; BIM adoption into curricular, Barriers in BIM education. The idea of researching other authors work globally forms a powerful form of analysis as to the approaches used in South Africa.

2.2.1 BIM adoption into curricular:

Over the past decade, BIM has been significantly implemented into schools of Architecture and Construction [6]. Focusing on earlier research, academics dwelled on the transition from 2D CAD to BIM [e.g 7,9,16]. However, recent studies dwell more on the actual use of BIM within the classroom at schools of architecture and construction [e.g. 2,5,14]. It is vital to understand how BIM is being implemented in curricular worldwide to determine the trend and methods of implementation. Pillay et al [17] conducted a study in South Africa on BIM use at South African construction schools and determined that very low levels BIM of implementation in the curriculum occurred, furthermore, lack of understanding of concepts became popular on the agenda. Similarly, Ahn et al [5] reports that students in Asia are more inclined to CAD use and most of the students have not experienced BIM technology.

Although various pedagogical approaches have surfaced in the implementation of BIM in university curricular, which methods are most sustainable? Ghosh et al [11] proposed a vertical systematic approach to implementation of BIM, through various years of study from basic to advance. Clevenger *et al* [8] suggests three methods; a stand-alone module, integrated BIM modules into current courses to develop BIM thinking and a combination of the two methods. The authors agree that all methods are noteworthy and can be implemented, however it is important to understand the barriers in BIM implementation.

2.2.2 Barriers in BIM education:

Like all pedagogical endeavors, BIM is subject to barriers that prohibit information dissemination. In this section the authors study the various sources of literature to determine some of the barriers facing BIM adoption and implementation at educational institutions. Some of the most common barriers facing BIM adoption into the curricular are Mindset in the process, Lecturers knowledge and training, complexity of software, equipment, time, lack of support from faculty etc. [8,11,1,3,17]. The issues facing BIM adoption in curricular are glaring and strategies to overcome them must be put into place. From various literature, a common thread is seen in implementation. Although various pedagogical issues arise, universities through the help of practice must ensure a smooth transition into acceptance and execution.

3. Research Methods

This research aims to discover the use of BIM at South African Schools of Architecture, in order to realize the research, question the authors propose the following method:

3.1 Task 1: Review of Literature

In this task, the authors conduct an extensive and critical review of literature of; BIM definition and BIM education in architecture schools.

3.2 Task 2: Research Methods

In this task, the authors opted for both a quantitative questionnaire and an interview-based approach of gathering data and understanding the current implementation of BIM. The research consisted of two groups of interviewees, namely students and lecturers.

The initial study sort to investigate responses from the 10 schools of architecture in South Africa, however due to time constraints not all schools participated in the study. Only 5 schools participated in the study. The schools that participated in the study yielded significant results to understand the BIM use climate in South Africa. The schools that participated in this study included: University of the Witwatersrand, University of Johannesburg, University of Pretoria, University of Kwa-Zulu Natal, and Nelson Mandela University. These schools offer a comprehensive program in architecture and are well suited for this research.

3.2 Task 2: Analysis of Data and Reliability

Data was collected from 5 schools of architecture over a period of 3 weeks. The Universities responded to a google form, telephonic interviews and a written statement of their feelings toward BIM implementation at their schools. From the various questionnaires sent to students and lecturers, the feedback from students resulted in 24 responses and 11 responses from lecturers respectively. The questionnaire comprised various methods of collecting data from checkboxes, linear scales to qualitative interview questions. Data was then examined using graphs. The reliability of data collected was based on a consistent questionnaire compared to interviews. Similar feedback from respondents suggest that the instrument is reliable, and data is true. The section of Findings and Discussion will explain the findings in thorough detail.

4. Findings and Discussion

In this section, the authors investigate a few aspects as described in the research methods, the first few questions are statistical data from interviewees after which the authors delve into the more pressing issues of BIM implementation and use at architecture schools in South Africa.

*4.1. Which school do you **study or teach** at?*

In this section, we discuss the statistical profile demographic of the respondents. The data from the questionnaires is significant in terms of understanding who the participants of the study are. It was noted from the responses that students from the University of Witwatersrand (WITS), Tshwane University of Technology (TUT), University of Free state (UFS), Durban University of Technology (DUT), Cape Peninsula University of Technology (CPUT), University of Cape Town (UCT) did not respond to the survey. Students that formed a major part of the study hailed from the University of Kwa-Zulu Natal (UKZN) at 29%, University of Pretoria (UP) at 33%, Nelson Mandela University (NMU) at 25% and University of Johannesburg (UJ) at 13%. Lecturers from the TUT, DUT, UFS, UCT and CPUT did not participate in the study. The UJ turned out to be the highest number of respondents at 55%, UKZN at 18%, UP, WITS and NMU at 9%. The significant number of both lecturers and students give the authors enough data to understand were the crucial issues of BIM implementation lay.

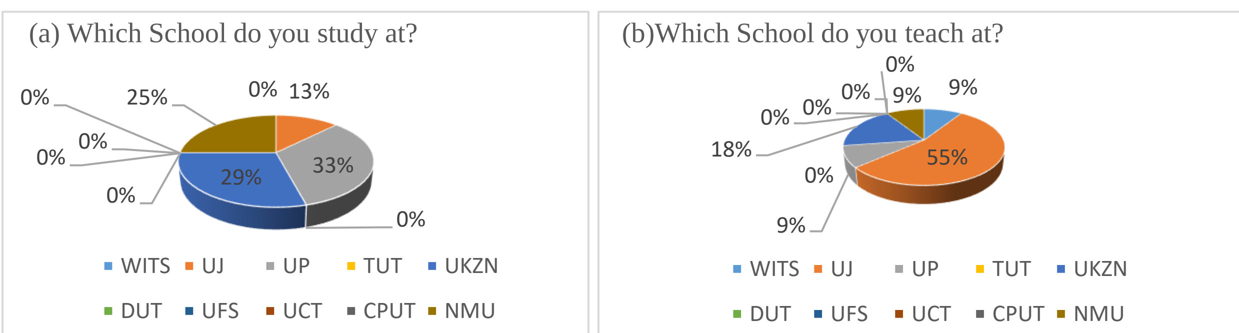

Fig. 1. (a) Students response; (b) Lecturers response.

*4.2. Which year level do you **study BIM at/ teach BIM** at?*

Although the questionnaire was sent out to various student year levels, only respondents in postgraduate levels responded to the it. It will be difficult to determine what the lower year levels require or are concerned about. However, the postgraduate students did respond in the interview and suggested how BIM should be taught holistically from the first year. 63% of respondents are in their final year of study (5th Year, Masters) and 37% of Students are in their 4th year of study (Masters). The lecturers on the other hand, revealed their various years of teaching BIM. Significant results prevailed from this demographic. 27% of participants answered in the negative to teaching BIM, however 18%

of respondents taught at 5th year level, 18% of participants taught at 4th year level, 19% of participants taught at 3rd year level, 9% of participants taught at both 1st and 2nd year levels respectively. This data reveals that there is a heavier emphasis of BIM education as the year level increases. There could be various reasons for this such as complexity of design work, workload, exit level outcome etc.

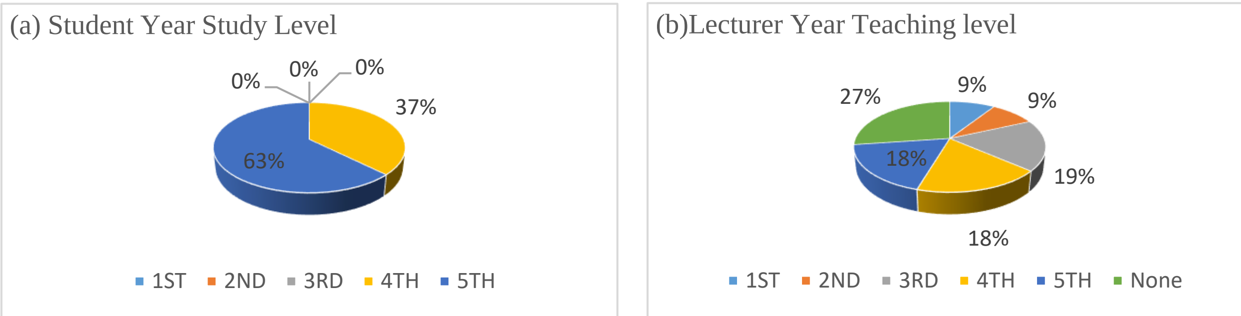

Fig. 2. (a) Students year level; (b) Lecturers year teaching level.

4.3. Do you currently make use of BIM?

When questioned about their current usage of BIM, students responded in the positive with 83% of the results being YES, 17% of students were unsure if they indeed used BIM. This result shows a significant use of BIM taking into consideration the year level i.e. Masters. Other students were unsure if they used BIM to its full magnitude, i.e. modelling, parametric information, analysis etc. The lecturers on the other hand showed significant responses both in the positive and negative, Lecturers answered YES to using BIM with 43% and 45% responded NO, 9% of the participants were unsure if they indeed used or make use of BIM technologies. It is important to note that half the demographic does not make use of BIM. This is indeed troublesome as it shows root cause of faculty staff which have not been trained with the likes of BIM.

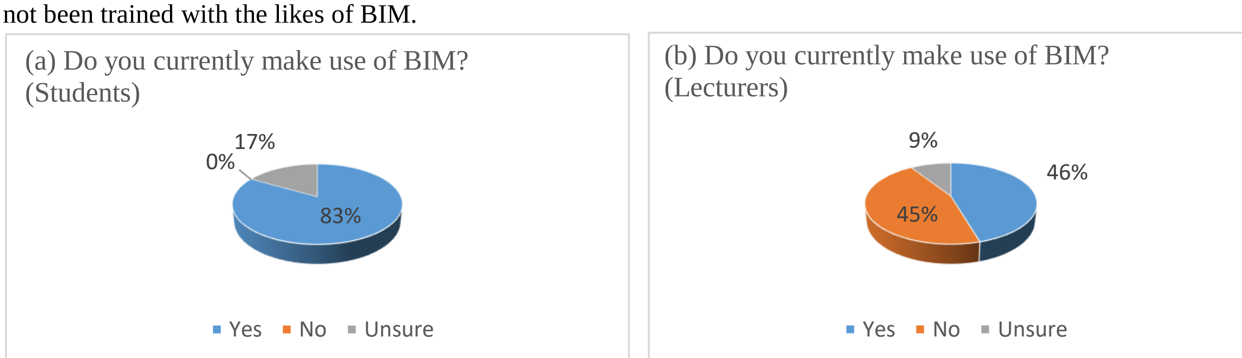

Fig. 3. (a) Students use of BIM; (b) Lecturers use of BIM.

4.4. Does your institution offer a BIM Module?

The authors probed the area of BIM module offerings. These results are by far the most troublesome. Students responded YES with 54% saying that their institution does offer a BIM module, 38% of students reported that their institution did not offer a BIM module, 8% were unsure. From the lecturers, a similar response was noted. 46% of lecturers reported that there was a BIM module in place. 36% of Lecturers reported that no BIM module existed at their department. 18% of respondents reported that they were unsure if a BIM module was available.

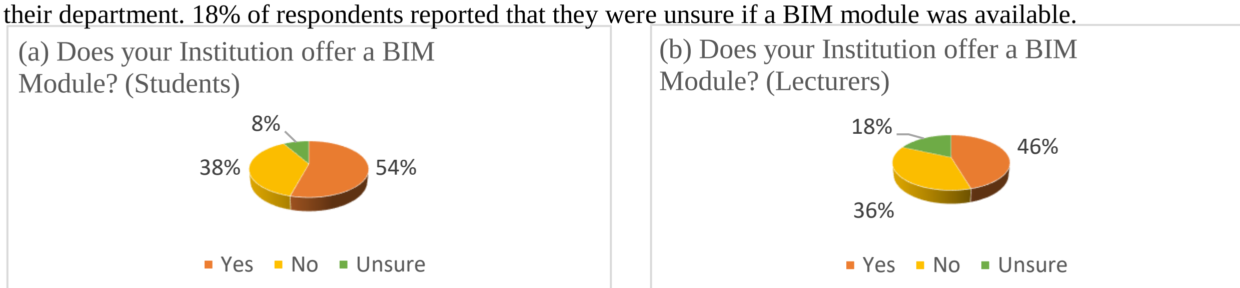

Fig. 4. (a) BIM Module - Students; (b) BIM Module - Lecturers.

4.5. In your opinion, Does the BIM process assist in understanding Design?

The process of understanding a design is a difficult one. The various parts and parameters of a building is complex, even on small projects. The authors sort to understand the opinions of both students and lecturers in this regard. A linear scale method of questioning was used, where 1 being strongly disagree and 5 being strongly agree. Referring to the provided graphs, the students tended to agree that BIM assists them in understanding their designs better, this is a significant finding as it leads to determining if BIM is truly helpful in design work. On the other hand, lecturers tended to disagree that BIM assisted in understanding design. This has been a popular opinion of Architecture academics throughout the world, it must be understood while the technology has not penetrated the older generation and possibly therefore, the lecturers are not fully aware of the capability of the software.

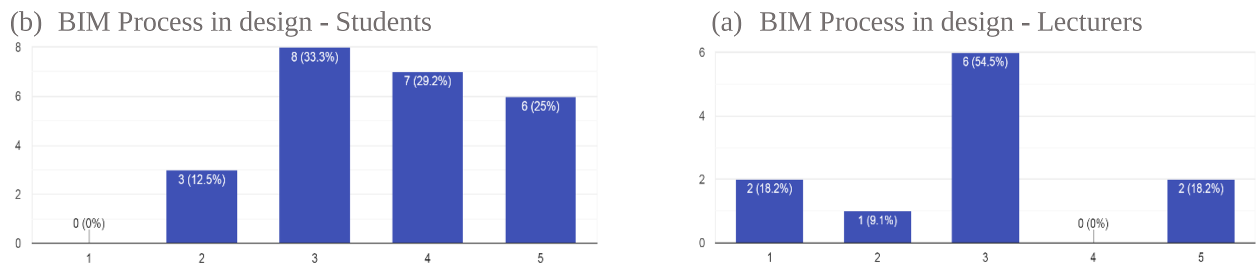

Fig. 5. (a) BIM process in design-Students; (b) BIM process in design - Lecturers.

4.6. In your opinion, does BIM hinder creativity when designing?

In all architecture schools, the process of creativity is not a rigid one, various theories and pedagogies exist in this space, however a common belief amongst academics is the BIM hinders creativity. The authors posed the question to both students and academics and the results are on either ends of the table. The results of this question revealed that students were almost neutral to the belief that BIM hindered their creativity when designing, however results leaned more towards agreeing that it hindered their creativity. This sets of results indicates that different students have different beliefs when it comes to creativity. The lecturers on the other end leaned toward strongly disagreeing, these results are interesting as it challenges the common belief from academics that BIM hinders creativity. The question posed to both students and lecturers is a very important one as the idea of using a BIM system to design a building is usually a challenge.

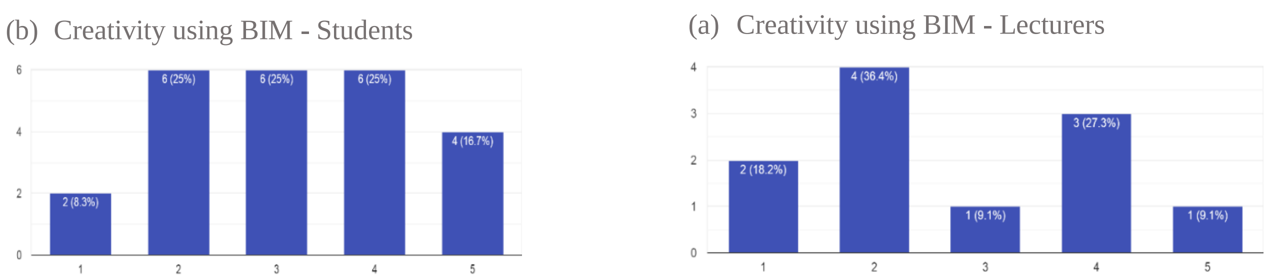

Fig. 6. (a) Creativity using BIM-Students; (b) Creativity using BIM – Lecturers.

*4.7 What could be improved so that you may better **learn / teach** BIM in the implementation of your design and construction courses?*

In this question, the authors asked as an open-ended question to both students and lecturers. The question sort to discover what was lacking in the implementation of BIM at the various institutions. The results obtained from the interview questions help understand the issues both from the lecturers and students. This will be analysed separately.

4.7.1 Students Answers

Below are some responses from students:

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"Teaching us the software earlier"

"BIM is very powerful and needs to be thought intensively from first year"

"Learn the software while engaging in studies at University"

"A more intensive module that is incremental throughout all years"

"The use of BIM will only actually be successful if you use more than one package and link the drawings together e.g. Revit and Dynamo. I also believe BIM was strictly designed for exchanging of information between different professionals by using something like Autodesk A360. As a student we won't ever be exposed to this except if it's a significant group project perhaps and all the students have access to a proper internet connection. I think South African's currently do not have the technical knowledge to implement BIM successfully"

"Students should be taught to use BIM as a tool when designing... it goes hand-in-hand with sketching and conceptualizing (a constant balanced process)"

"Better lectures to learn to use the technology properly so it doesn't hinder your design possibilities"

"Consider alternatives to the usual process any student goes through after a brief, in most cases its design focused and construction (tech) is the last thing on your mind, perhaps by altering the brief to reward technical prowess we can encourage design that is rooted in reality and becomes more unique as a result of this process"

Analysing the comments from students, some glaring issues are revealed. Issues pertaining to being taught the software earlier on in the academic programme seems to be a lingering issue, both in South Africa and the world over. This is a common theme and should be investigated carefully to allow for students to learn software earlier on in their course. The issues of teaching BIM as an exchange of information is also a critical issue, BIM is usually taught as a standalone package that is geared specifically towards modelling of a building. This must be investigated further and allow for an exchange, even with other disciplines in an academic setting. An issue that is very prominent with students is the issue of design and BIM, students prefer BIM as a tool when designing, to resolve problems as and when they occur. An integrated course geared to real world issues is also another issue, students finishing their courses must be prepared to take on the challenges faced in the practice. The issue of faculty staff being trained well to teach BIM is an ongoing issue, in this study and many others; lack of trained stuff is one the major issues universities around the world face.

4.7.2 Lecturers Answers

Below are some responses from lecturers:

"better learning and interaction spaces"

"The availability of text books and concepts"

"More time is needed to teach the principles and use."

"attempt to get students on top of the software as quickly as possible so that they can control it rather than it controlling them"

"Integrated learning of BIM within design briefs"

"If we had a BIM lecturer. We need more time to teach BIM"

"Include BIM in the curriculum"

Through analysis of comments put forward by lecturers, some interesting facts are revealed. Lecturers are often faced with the need for facilities to teach BIM, by far many comments from teaching staff lead to the lack of facilities. Universities should try to include the various facilities needed to teach BIM, which includes but not limited to space, equipment and learning materials. Integration into the syllabus is also an important comment received, this will assist or accelerate the learning of BIM within the architectural learning space. The comment that stands out between both students and lecturers is the availability of teaching staff that are highly skilled in BIM. The universities should look at external service providers or candidates from practice to fill in the role of BIM lecturer.

4.8 Barriers affecting BIM Implementation at South African Schools of Architecture

Table 1. Barriers and Recommendations for implementing BIM in order of Importance.

Barriers	Recommendations	Effort Level
1. Integration of BIM into Curricula.	A strong implementation strategy must be developed, for e.g. BIM components in each project as a non-negotiable element, Marking rubric to include BIM elements, Stand alone courses which focus specifically on BIM, BIM implementation must occur from the first year of study to promote and grow the knowledge of students.	**10**
2. Trained Lecturers in BIM.	The need for staff that are trained and specifically advancing their own knowledge in BIM must be non-negotiable. This component is critical for advancement of student and institution knowledge and advancement. Furthermore, support from BIM teaching staff will give students confidence to advance their knowledge, not only in BIM but design and construction technology.	**10**
3. Mindset.	The idea of BIM being a hindrance to students is a misnomer, Faculty and students must embrace the technology which will ultimately benefit both parties. A thorough introduction and discourse into the advantages of BIM needs to be understood to further reinforce the positive benefits.	**8**
4. Availability of space and equipment.	Space and Equipment is vital for the discourse of BIM. Space must be a high priority. The equipment to teach and learn BIM is also of high priority, during this study, it is noted that equipment becomes a significant barrier facing both students and lecturers. It is recommended that the Faculty place this as an ongoing budget to keep equipment up to date.	**8**
5. Time.	Time to teach, learn and practice is crucial for the advancement of BIM knowledge at universities. Architecture departments must increase the time allocated for training of students with BIM products.	**7**

The above table gives an insight to the top five barriers affecting the implementation of BIM at South African Architecture schools in order of importance. The authors have further used a rating of effort from 1 to 10, 1 being; little effort and 10 being major effort. Through the questionnaire and interviews, the above, self-explanatory table is used to disseminate the barriers facing architecture schools about BIM implementation.

5 Conclusion and Recommendations

In this section the authors provide conclusions pertaining to the findings in both the literature and empirical data provided in this research. It is critical that these findings be taken seriously if South African Architecture schools wish to pursue a strong BIM output from their curriculum. For this research, the authors intended to discover the level of BIM implementation at South African Schools of Architecture, the study is aimed at gathering data to determine where South African Schools of Architecture currently stand in terms of implementation. Although this study was relatively small, it shows significant representation of common beliefs both amongst students and lecturers.

From literature and empirical study, the authors determine various barriers which prohibit the dissemination of knowledge. For the successful integration of BIM into architecture schools, the various factors must be taken into consideration as a matter of urgency. For immediate effect, the authors propose that courses be structured to integrate

BIM as a component of both design and construction technology to allow students to get grounded knowledge and to advance their discourse simultaneously. By adopting BIM into the studio, the integration will allow for further introspection and learning. Furthermore, trained staff can assist students with BIM in a studio environment to realize their projects which hold much value compared to basic hand and CAD drawings. The authors suggest this mindset to advance the students capabilities and adopt a holistic approach in their specialty. This approach will assist in the issues of time as an integrated approach will allow for more time were students are able to practice both BIM and architectural work.

The authors find commonality between South Africa and other countries in terms of BIM implementation at institutions. However, the authors suggest further research in this area to include other countries for two reasons; one to determine the level of implementation of BIM at institutions and two; to determine what strategies have been employed to implement BIM. This approach can lead to a larger debate in which appropriate solutions to implement BIM in university curricula can be adopted.

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Feasibility Study of Integrating BIM and 3D Printing to Support Building Construction

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Abstract

Although BIM has already been used to detect, simulate, and display construction details in many construction projects, these operations are performed and viewed exclusively on computers rather than on actual construction sites. In other words, when engineering staff holds meetings to discuss construction details, they are still required to use their imagination because they have no actual objects to refer to. Accordingly, they may be unable to correctly implement the construction details on actual sites, diminishing the benefits of BIM.

3D printing technology is becoming increasingly mature. In recent years, the construction industry has also frequently discussed the use of 3D printing technology. Scholars have indicated that combining BIM and 3D printing technology will be one of the future directions for expanding the use of BIM. Nevertheless, when examining the application of 3D printing, the construction industry has often focused on large-scale printing (e.g., printing the entire house). By contrast, this study, which integrated BIM and 3D printing technology, used a small version of the 3D printing model to review operations that were difficult to discuss through imagination (e.g., how to solve interface conflicts and assemble precast components). By using this 3D printing model, engineering staff could examine and assemble actual components at the construction sites, thereby facilitating the construction work. In short, by utilizing the BIM to produce 3D printing models and components, and using said models and components as the basis for construction site-related discussions, engineering staff may be able to elevate the overall construction results.

This study examined whether integrating BIM and 3D printing technology was a feasible option for helping building design and construction. Furthermore, this study investigated how BIM could be used to quickly generate 3D printing models and the effectiveness of using 3D printing technology to print actual components during the construction process.

Keywords: 3D printing, building information modeling, construction details.

1. Introduction

On-site construction projects require the engineering staff to discuss numerous details of construction implementation methods. Such negotiation involves topics such as interface conflict solutions, steel bar binding methods, precast component assembly, and beam casing methods. Failure to address in advance the construction details for on-site implementation may result in progress delay and cost increase.

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The rapid advancement of computer information and communication technology in recent years enables building data to be digitalized through building information modeling (BIM) based on a basic three-dimensional (3D) structure. Such modeling can automatically generate geometric and nongeometric parameter characteristics of building components, thereby gradually drawing attention from the engineering industry and academia (Chen, 2009; Guo and Hsieh, 2010; Zhang and Hu, 2011). Numerous construction projects have benefited from the assistance of BIM by conducting assessments, simulations, and demonstrations of construction details on computers. However, the model has yet to be physically implemented. That is, engineering crews still must rely on partial guesswork when attempting to decide the implementation details during meetings. Lacking a sense of concreteness, engineering crews may not be able to follow precise procedures on-site, thereby limiting the benefits of BIM.

The technology of 3D printing has become increasingly mature. Because of its high degree of customization, fixed cost, and short completion times, 3D printing technology has been widely used in the construction industry in addition to the medical and manufacturing industries. However, past discussions of the aforementioned combination have usually focused on large-scale printing (e.g., printing an entire house) as the research direction, whereas this study used miniature 3D models to examine the actual implementation steps of construction projects that are difficult to visualize during discussions, such as addressing interface conflicts and precast component assembly methods. Miniature 3D printing models enable the actual assembly or examination of components on a construction site, effectively assisting in the process of construction. That is, if the BIM models and components can be output as 3D-printed models as the basis for discussion on the construction site, the overall construction project performance should be improved.

Therefore, this study explored the feasibility of integrating BIM with 3D printing technology to assist in the design and construction of buildings. In addition to exploring how to 3D print models rapidly from BIM models, the present study also investigated the effectiveness of 3D-printed solid components on improving the convenience of project implementation.

2. Literature Review

2.1. State of 3D printing

The technology of 3D printing originated from rapid prototyping technology. In 1981, two 3D-printing methods were first proposed. In 1984, US 3D Systems founder, Chuck Hull, developed 3D rapid prototyping technology. The first patented 3D printing technology was applied by the Massachusetts Institute of Technology in 1989. It was not until 2010 that related applications of 3D printing began to develop.

The present applications of 3D printing are only mildly customizable and focus particularly on unique shapes and products that are difficult to process through conventional techniques. Future businesses may adopt high-value but a low quantity of tech products. In terms of applications of 3D printing in engineering projects, numerous laboratories have begun to adopt the technique for small objects (Misao, 2014). Apis Cor, a San Francisco–based startup company, printed a complete circular building including a living room, a bathroom, and a bedroom in less than 24 hours using concrete; the building cost approximately US$10,000 (Tu, 2017). Behrokh (2012) also revealed that 3D printing will eventually be able to complete building construction in less than 20 hours. The incorporation of 3D printing techniques can substantially reduce the production time of building components. Using printed components as references, engineering crews may discuss precast component assembly methods, steel bar binding methods, and interface conflict solutions during their meetings.

2.2. Applications of BIM and 3D models in construction projects

Chen and Tsai (2015) assisted in the maintenance and management of construction projects using 3D printing. They developed a 3D printing–based building maintenance system, in which building information is stored in advance in a database. Subsequently, a platform they developed was used to extract parameter information to establish a 3D printing model of a building, which was then printed for assembly.

You (2017) combined virtual BIM and a 3D solid model for virtual and physical integration. The 3D model of that study project was obtained through fused deposition modeling with polylactic acid as the material. However, some components in the study project still had loose joints. Some components still could not be 3D printed and thus were replaced with other materials such as fishing lines.

3. Method of integrating BIM model and 3D Printing

Although BIM has already been used to detect, simulate, and display construction details in many construction projects, these operations are performed and viewed exclusively on computers rather than on actual construction sites. In other words, when engineering staff holds meetings to discuss construction details, they are still required to use their imagination because they have no actual objects to refer to. Accordingly, they may be unable to correctly implement the construction details on actual sites, diminishing the benefits of BIM.

3D printing technology is becoming increasingly mature. In recent years, the construction industry has also frequently discussed the use of 3D printing technology. Scholars have indicated that combining BIM and 3D printing technology will be one of the future directions for expanding the use of BIM. Nevertheless, when examining the application of 3D printing, the construction industry has often focused on large-scale printing (e.g., printing the entire house). By contrast, this study, which integrated BIM and 3D printing technology, used a small version of the 3D printing model to review operations that were difficult to discuss through imagination (e.g., how to solve interface conflicts and assemble precast components). By using this 3D printing model, engineering staff could examine and assemble actual components at the construction sites, thereby facilitating the construction work. In short, by utilizing the BIM to produce 3D printing models and components, and using said models and components as the basis for construction site-related discussions, engineering staff may be able to elevate the overall construction results.

4. Case study

This study took a steel-pipe dam as an example and output a 3D-printed model from BIM to evaluate the feasibility of combining BIM with 3D printing, thereby investigating the benefits of 3D printing for construction projects. The steel-pipe dam utilized a new construction method. Precast steel pipes were assembled on the river during construction to maximize the convenience of installation. This study 3D printed a model of the pipes of the dam and discussed the assembly method in advance to ensure the efficiency of on-site assembly.

Testing revealed that the 3D solid model might not be able to present the details of the engineering facilities if the model scale was reduced. An excessively large output scale (e.g., 1:50) would require the printing process to be split into multiple parts to display facility details. Moreover, storing large 3D models may be a problem. Therefore, the appropriate printing scale for 3D models is a topic that requires further discussion. The printing procedure of converting BIM components into a solid 3D model involves the following nine steps. The BIM model of the steel dam is shown in Figs 1 and the printed steel pipe in this study is presented in Figs. 2-3.

(1) Establish a highly precise BIM model for soil and water conservation projects (including engineering facilities and topography).
(2) Launch Revit and export the Revit file.
(3) Import the Revit file into 3ds Max, from which the stereolithography (STL) print file is exported.
(4) Import the STL file into Autodesk 123D:
  a、Perform model patching: Fix, check, and repair the loose joints and errors in the model.
  b、Set the model output scale.
  c、Cut the model according to the 3D printer’s output scale; each model after cutting is output as an individual STL file.
  d、Examine each STL file and select the optimal model plane as the bottom for printing. All files are saved afterward.
(5) Calibrate and warm up the 3D printer, and then set the print quality.

(6) To avoid the wires prepared by hot melt extrusion failing to stick firmly to the platform of the 3D printer during the printing process, this study placed temperature-resistant masking tape on the platform and applied glue from a glue stick to increase the adhesion of the wire.
(7) Select an STL file to conduct a printing test.
(8) Examine the quality of the solid 3D model after printing. If the crucial details cannot be observed, the printing scale must be adjusted (i.e., the fourth step must be repeated). The printing test is performed repeatedly until the model meets the requirements.
(9) Print the BIM components according to the appropriate scale determined by the printing test.

However, the proposed method of converting BIM models into 3D-printed models still requires modifications because it could not rapidly generate the required models through 3D printing.

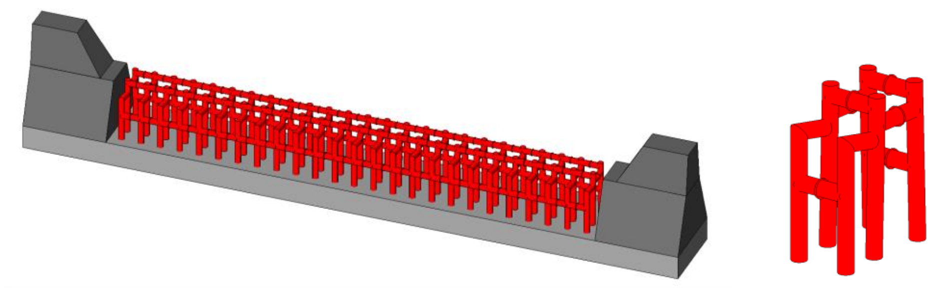

Fig. 1. (a) BIM model of steel-pipe dam (b) BIM model of steel pipe.

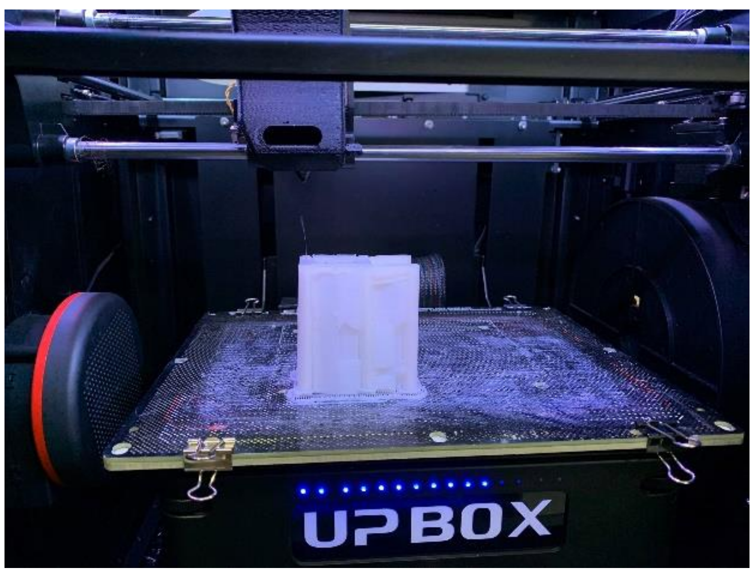

Fig. 2. printing the 3D model of the steel-pipe dam.

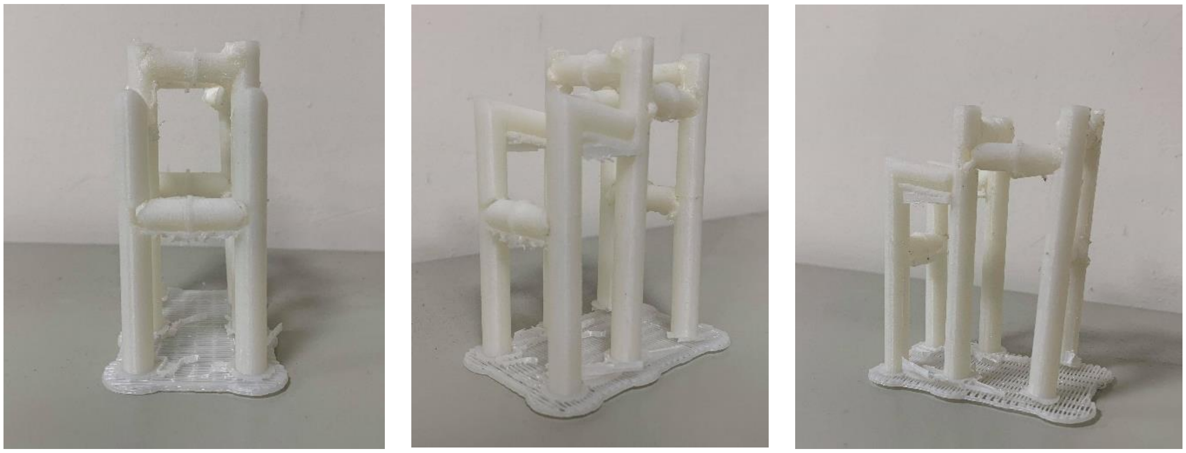

Fig. 3. part of 3D printed steel pipe.

4. Conclusion and Suggestion

This study attempted to integrate BIM with 3D printing to explore a method for converting building data into 3D models using BIM software, Revit. The obtained model was conducive to evaluating the feasibility of construction project implementation. The experiment in this study revealed that direct conversion of BIM ideas into a 3D model may reduce the time required for 3D model construction and may allow engineers to perform model modifications and printing directly.

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Lifecycle Design of Fastening Systems in Concrete Supported by BIM: Case Study Subsequent Assembly of an Industrial Robot

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Abstract

In the last years, particular focus has been devoted to the life cycle performance of fastening systems, which is reflected in increasing numbers of publications, standards, and large-scale research efforts. Simultaneously, experience shows that in many cases, where fastening systems are implemented – such as industrial facilities – the design of fasteners is governed by fatigue loading under dynamic characteristics. In order to perform an adequate design and to specify the most efficient and appropriate fastening product, the engineer needs to access and process a broad range of technical and commercial information. Building Information Modeling (BIM), as a data management method in the construction industry, can supply such information and accommodate a comprehensive design and specification process. Furthermore, the application of BIM-based processes, such as the generation of a BIM-model, allows to use the important information for the construction as well as the life-cycle management with different actions and time dependencies of the asset and its components. As a consequence, the BIM model offers the potential to correlate different data relevant for achieving the goals of the respective application, in order to ensure a more effective and correct design of the fastening. This paper demonstrates such a BIM-based design framework for an Industry 4.0 case, and in particular, the installation of a factory robot through post-installed anchors under fatigue relevant loading in concrete.

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Keywords: Building Information Modeling; Fastening Systems; Fatigue Loading; Industry 4.0; Lifecycle Design;

1. Introduction

Building information modelling (BIM) is vividly gaining scope of application in the construction industry, which is evident in numerous publications of academic studies, case studies, national and industry standards, and in dedicated technical events. BIM presents a variety of benefits in several aspects of infrastructure engineering, most eminently with respect to project coordination during the planning and construction phase, and the facility management during building operation. The privilege of relying on BIM for the life cycle management of technical assets is currently a focus in the discourse of digital planning and construction. In particular, archived BIM models can accommodate efficient processes for locating the component of interest, evaluating it's remaining service life, assessing costs of

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maintenance or replacement, and coordinating inspection and maintenance exercises at a project level. Modern industry currently begins to support dynamic interactions between the digital and hardware or built environment (e.g. IoT systems), based on a combination of live multidimensional BIM models connected in a network of data transfers and processing. Recently, research in the field [1], [2] has achieved to transfer building facility management exercises to the Industry 4.0 realm, by coupling building with factory operation datasets, thus opening the potential for further integration of various technical and industry disciplines to multidimensional BIM objects [3].

At the same time, connections and fastenings are a key element in the construction sector. As a critical and repetitively used component in construction, fasteners, are required to exhibit a consistent life cycle with the respective fixture. Sensitivities to a fastening system's life-cycle performance are associated among other to assembly/decommission flexibility, accessibility, load-bearing capacities under dynamic, seismic, or sustained loads, and environmental specifications such as thermal and noise insulation, fire resistance, material resources [4]. Human errors at installation are very common and they can consume even the entire load-bearing capacity of the fixing, well before the intended end of service life. The potential loss due to system losses caused by failed fastening elements is by several orders of magnitudes higher than the value of the product itself. Therefore, for structural connections, the entire structure's design service life must be maintained also for fastenings and for attachments of technical equipment, performance of the fastening is essentially a precondition for the operation of the equipment. Highly significant attachments are those associated to human life and safety (lifeline equipment, suspended building furniture, etc.), or to a substantial economical value (such as machines or robots in factory production lines). This study focuses on this latter case, and it presents a life-cycle approach of fastenings in the environment of modern automatised industry production.

In particular, this case study highlights the relevance of BIM modelling for an improved design and life cycle assessment of fastenings. The concept is presented in terms of an Industry 4.0 case study, with focus on the foundation of a robotic arm susceptible to fatigue failure. Factors significant for the short-term and fatigue design of the fastening are extracted from an enhanced BIM object, where both building as well as operational data are stored [5]. The necessary input data are described, they are converted into compliant forms, and they are used for a structural design based on realistic actions on the fastening. Moreover, the flow of live information is used for an effective prediction of the fastening's service life, allowing for an educated maintenance strategy. In parallel, this study demonstrates a holistic use of BIM in operating Industry 4.0 components, coupling production and building management of factory assets.

2. Structural characterization and designing of fastening systems

For the structural dimensioning of fastening systems, designs procedures are carried out according to currently valid models in the standards. The newly issued Eurocode for fastenings, EN 1992-4 [6], is the applicable reference standard in Europe and largely implemented worldwide.

The structural design is typically done on the basis of action and resistance, i.e. assessment and comparison between the properties of the fastening system and the performance requirements. Actions are typically categorised through the following aspects:

- Mechanical action types (quasi-static action, fatigue relevant action, seismic action, temperature, etc.)
- Temporal course, values of the action and behaviour of the load
- Geometric direction of action (axial, transverse)

As regards fastening system properties, the following elements must be accounted:

- Fastening group or individual fastening
- Geometry (edge distances, spacing between fasteners, fastener diameter, embedment depths, etc.)
- Materiality of fastening (concrete class, mortar, plastic sleeves, steel class, etc.)
- Mechanical resistance and load transfer mechanism (friction, bonding, mechanical interlock)

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The performance of the system is mainly described in a publically controlled product specification, the so called European Technical Assessments (ETA), and it is also officially guaranteed thereof. This document generally includes the products material and geometry, the setting procedure, geometric boundary parameters and the final mechanical resistances [7].

The mechanical actions can be quasi static, dynamic (fatigue-relevant, seismic, impact), or a random combination thereof. The fatigue-relevant actions, respective non-resting actions, upon which this case study concentrates, are subdivided into different components, depending on their time-history, whereby periodic and harmonic functions typically resulting, for example as the effect of unbalances of rotating machines [8]. Above all, the identification and differentiation of fatigue-relevant loads and the level of simplification of the motion and load history has a substantial effect on the design, i.e. the utilisation and economic efficiency in combination with the lifetime analysis. Especially in the case of fastening robots, which can deliver an exact, three-dimensional load and force profile, the conventional approach of sinusoidal independent functions has its limits in terms of feasibility and economic efficiency. Detailed considerations and associated calculation paradigms, accounting for an aggregation of multiple simultaneous loading data, are shown in the following chapters using the case of the fastening of a robot.

3. Building Information Modelling (BIM)

A BIM is a digital representation of physical and functional characteristics of a facility. As such it serves as a shared knowledge resource for information about a facility forming a reliable basis for decision during its lifecycle from inception onward. If implemented, nearly every piece of information that an owner needs about a facility throughout its life can be made available electronically. As Fig. 1 illustrates, the BIM method is separated from conventional planning methods at the point from planning in three dimensions by using just geometric data to three dimensions combined with other information e.g. data like quality information or maximum loads. At this stage it turns from a building model to a building information model, where information about time and costs are associated into the fourth and fifth dimension.

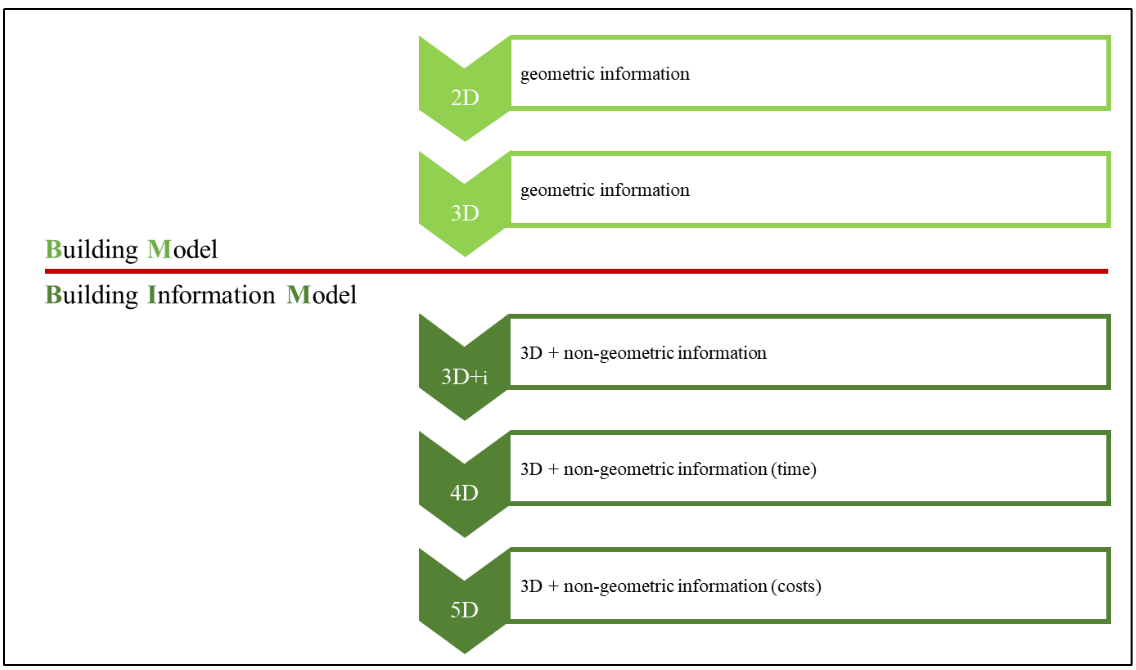

Fig. 1. Building Information Modelling vs. conventional planning.

4. Data utilization for life cycle design

In order to determine whether there are efforts by using data it is necessary to examine the existing data base of the several parts. This section describes a case study with three different objects of investigation (robotic arm, fastening system, building slab) as illustrated in Fig. 2. Table 1 summarises the relevant data from the BIM model, for every different module.

The floor slab was created within a BIM-Model, as a main module with six submodules. The submodules are: coating system, concrete floor slab, sealing, smoothing layer, base, and underground. By designating the individual sub-modules, it is possible to filter out data from a higher number of influencing and relevant information, and to localize dependencies between all further modules and sub-modules. Furthermore, geometric and non-geometric properties of the slab module are assigned.

The fastening system is also created as a flexible recurring module with both geometric and non-geometric information. Some of these data are associated to the products ETA. As mentioned above, critical for the design are the actions on the fastening resulting from the kinematic history of the fixed element (robot). The movement of the robot and object happens elliptical in space, i.e. a complete rotation around its own axis with vertical displacement of the robot arm (see also Fig. 3). The fatigue assessment is then carried out for 1 million cycles, representing the service life of the robot.

The robot used in this case study, is Motoman MH50 II of Yaskawa. The robot coding data are conveyed to the BIM model which is then connected to the fastening technology design algorithm in order to provide the automated dimensioning. A warning trigger is also be assigned for the case that the ultimate capacity limit state of the fastening system is approached, at a characteristic 75% by load cycles.

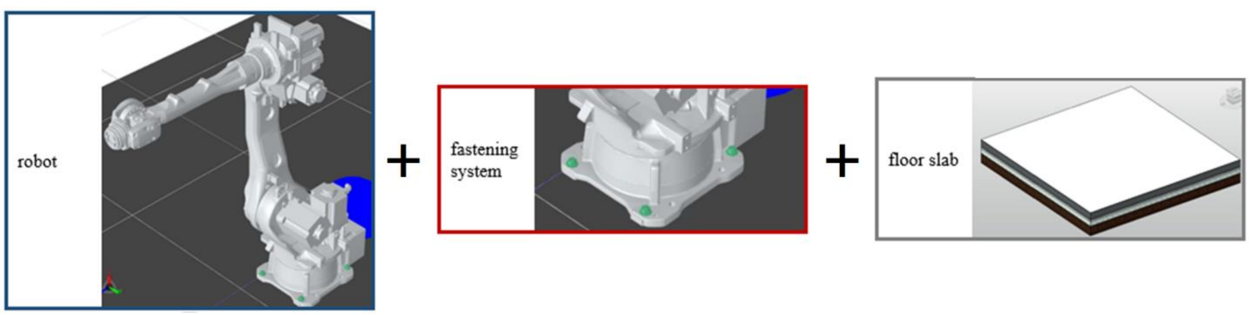

Fig. 2. Objects of investigation

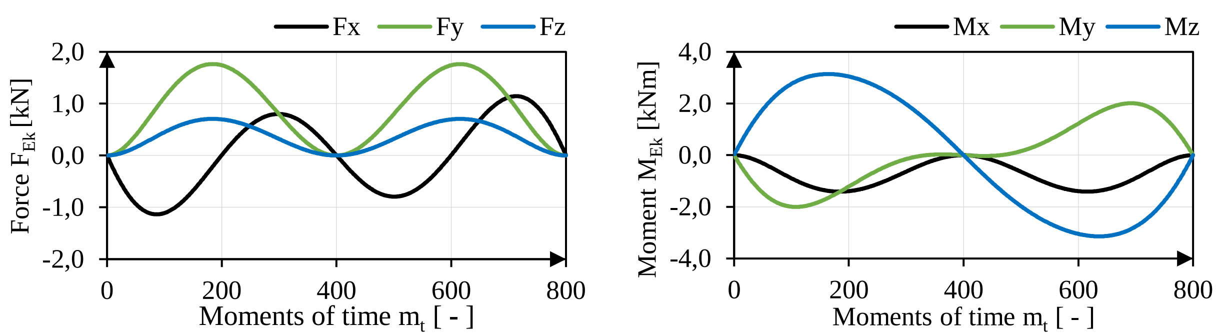

Fig. 3. Force (left side) and moment (right side) histories for the motion of the robot. Two cycles are define in this period of loading, from 1 to 400 and from 401 to 800.

Table 1. Summary of data related to the BIM model, distinguishing material and geometrical parameters used in the structural design (light green) and elements related to the production and the associated robot kinematics (dark blue).

subsystem	name building part	building part ID	parameter	value	unit
supply of the machine	factory area	electrical supply	installed load	4,0	kVA
networking of the machines	factory area	data supply	# of data supplies	1	-
networking of the machines	factory area	wireless lan	wireless lan available	affirmative	-
supply of the machine	factory area	compressed air supply	compressed air supply necessary	negative	-
supply of the machine	factory area	compressed air supply	compressed air	-	-
fastening of machines	foundation area	fastening system	anchor diameter	16	mm
fastening of machines	foundation area	fastening system	borehole diameter	18	mm
fastening of machines	foundation area	fastening system	anchor embedment depth	125	mm
environment of the machines	factory area	heating / air-conditioning	maximum temperature	45	°C
environment of the machines	factory area	heating / air-conditioning	minimum temperature	0	°C
environment of the machines	factory area	heating / air-conditioning	maximum humidity	80	%
environment of the machines	factory area	heating / air-conditioning	minimum humidity	20	%
floor space of the machines	foundation area	floor slab	weight of the robot	550	550 kg
floor space of the machines	foundation area	floor slab	maximum load capacity	50	50 kg
floor space of the machines	foundation area	floor slab	MR maximum torque	216	216 Nm
floor space of the machines	foundation area	floor slab	maximum moment of inertia	28	28 kg x m²
floor space of the machines	foundation area	floor slab	concrete quality	C30/37	-
floor space of the machines	foundation area	floor slab	minimum width foundation	-	-
floor space of the machines	foundation area	floor slab	minimum length foundation	-	-
floor space of the machines	foundation area	floor slab	minimum thickness foundation	160	mm
floor space of the machines	foundation area	floor slab	minimum edge distance dowel	210	mm
floor space of the machines	foundation area	floor slab	concrete cover	35	mm
floor space of the machines	foundation area	floor slab	reinforcement spacing longitudinal	150	mm
floor space of the machines	foundation area	floor slab	reinforcement distance transverse	150	mm
floor space of the machines	foundation area	floor slab	reinforcement diameter	10	mm
floor space of the machines	foundation area	floor slab	reinforcement Steel grade	B500B	
floor space of the machines	foundation area	floor slab	distributed load	5	kN/m²
floor space of the machines	foundation area	floor slab	single loads	7,5/216	kN / cm²
floor space of the machines	foundation area	floor slab	evenness	DIN 18202, table 3, line 4	-
floor space of the machines	foundation area	floor slab	surface	smoothed	-

5. Integration of asset, structural, and production data in a BIM-based design

The calculation and processing of information of the action and characteristic values of the fastening system in the current design models and concepts is based on simple empirical/physical equations, which require a certain level of engineering knowledge and define many sub-cases for correspondingly limited and special design cases. A generally valid design under consideration of various possible boundary conditions is not feasible. The advanced design concept, used in this case study, for a fastening systems under fatigue-relevant loading covers for the generic or initially random nature of the actions, and it allows for a time-independent and multi-dimensional design. This is realized by a transformation to utilization levels with the high combinatory of various time considerations, so that also an integration to BIM compatible data formats is possible. For the analysis of different design situations, the force and moment

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information from Table 1 and Fig. 3, is used as the basis for describing the motion sequence with the real actions. In comparison to these exact courses, approximations are also used and analysed in the form of sinusoidal functions. Here, the minimum and maximum points in the sinusoidal course are determined equivalent to the extreme values of the real action. A further variation in the investigation of the design concepts is the number of differentiated time moments. In this study, 30, 60, 90, 240 and 360 values are also used and examined. The influence of this design option is to be carried out and analyzed with the comparison between the separate consideration of both cycles and the conventional duplication of the unfavorable course. The design check has indicated the most unfavourable design situations, so that on the one hand for steel failure a higher utilization results by conventional designing with 1 load-cycle (1 to 400 or 401 to 800) and the double number of cycles. The variant with previous approximation with sinusoidal functions shows a reduction of the steel failure and a significant increase in the case of concrete failure.

6. Conclusion and outlook

The support of a BIM-model in the design process of fastening systems offers the advantage of an automated and real-time based evaluation of the selection of fastening systems. Interactions and boundary conditions (conflicts) can also be automatically checked. Structural information must be digitised from ETAs in advance, in order to enable processing of quantitative and qualitative values. Furthermore, efficient and user-friendly program structures and software solutions must be developed to be able to process this information in fast computing processes. The categorisation and integration of data is showcased herein. This conceptual process is further proposed and a design example is also shown in order to verify the feasibility of the concept, with focus on life cycle relevant design situations.

An approach for automatic integration of various program sequences into a BIM model could be prospectively based on the solution for flexible robot programming via drag and drop (also refer to the example in [9]). This solution enables a new form of robot programming, so that the functions and program sequences of the robot can be easily defined via a modular system, independent of manufacturers and without programming knowledge of the user. This concept offers the potential to harmonize the problem of differences in programming and could thus offer an efficient interface to a BIM model for the automatized capturing of data from the production program. Conveyed to a Industry 4.0 environment, the planning and facility management exercises, assisted by sensors and programmed warning features can allow for a full integration of asset and production management.

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Linking Revit Facility Life-Cycle Data to ARCHIBUS – A Case Study of an Academic Institution

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Abstract

Building owners and facility managers are beginning to leverage spatial information and asset data in BIMs for efficient and sustainable building operations and maintenance. Extracting information from BIMs for import into FM platforms still poses an implementation challenge to many owners. Methods for bi-directional synchronization of data between a BIM and FM software for real-time access to lifecycle model data can be more advantageous over one-way data export approaches so the owner can take advantage of an as-built BIM that can have data updated in real-time with continuous asset data updates. This paper uses a case study of a renovation project on a university campus to illustrate the use of the ARCHIBUS Smart Client for bidirectional real-time data exchange with Revit. The Archibus workflows were compared to other methods for data exchange as to how they support the needs of the owner. Lessons learned and challenges related to this workflow are discussed.

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Keywords: Building Information Modeling; Facility Management; Revit; Archibus; Asset Properties; Life Cycle Data

1. Introduction

The number of building owners and facility managers needing to leverage spatial information and asset data in BIMs for efficient and sustainable building operations and maintenance continues to be on the rise. From a 2014 report, owners requested that BIM be used on 49% of the projects but only 25% of the owners in the survey required BIM to be used. In the same study, owners' involvement with BIM rose over a two-year period from 42% to 59% and was expected to continue to grow while expanding the level of involvement linked to BIM on the project [1]. Linking BIM data from the model to the FM system has proved very valuable as it reduces time and effort on the facility manager and allows for supporting immediate and efficient use of the CMMS prior to occupying the building [2]. This fosters more efficient work order management and building maintenance activities.

Extracting information from BIMs for import in FM platforms still poses an implementation challenge for many owners due to various barriers including lack of in-house technical skill, cost of system implementation, personnel or resource limitations, and lack of knowledge [3,4]. Proprietary BIM add-ins (or plug-ins) that provide direct synchronizing of BIMs with the FM software, including CMMS and IWMS systems, for real-time access to life-cycle model data provide an advantage over other solutions that use one-way data export approaches.

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This research resulted in the development of BIM-FM guidelines for a large educational university. Completed phases include data needs analysis and documenting the data into a Revit model. This paper examines one of the approaches explored to transfer the data from a Revit model into a CMMS for FM asset management.

1.1 Information transfer

Traditional workflows to get facility information into the owner's CMMS system use manual error prone processes that are time consuming and results in incorrect and incomplete information [5]. Using BIM as a data source to document facility information for post-construction use was proposed to streamline the workflow to get information into the CMMS in a more effective manner.

Prior research identified the information needs for the owner [6] and pilot tested electronic means for documenting the information through custom parameters within Revit [7]. In total, 80 assets are tracked by the owner with common parameters and customized attributes. Facility data is collected at various phases through construction to be supplied to the owner. Methods explored for data documentation included direct input into Revit schedule, the use of Navisworks DataTools, and third party plug-ins. Each method resulted in exporting schedule data from Revit into a CSV file, manipulating the file, and using Pentaho to map the data to appropriate fields with the CMMS.

The current phase of the research is exploring methods of reducing manual manipulation of the data. Three basic methods were explored as part of this research [8]. The first was to use Navisworks DataTools to document and track additional information and export data. The benefit of this method was an as-built model that can store structured and unstructured data through hyperlinks to related documents. The second method was to use Dynamo within Revit to create a customized workflow. Required information from the model was captured by the workflow and documented into an Excel spreadsheet in the required format that can be directly linked to the CMMS. In addition, the documentation of Dynamo to directly link the data to the SQL database and remove additional mapping needs was also explored. The last method was to explore the use of ARCHIBUS Smart Client and the corresponding Revit plug-in to examine bi-directional data transfer between the Revit model and CMMS. The ARCHIBUS Smart Client workflow, challenges faced, and lessons learned are discussed in more detail in this paper.

1.2 ARCHIBUS Smart Client and Extension for Revit

ARCHIBUS is an enterprise asset management solution that provides asset lifecycle and maintenance management for all types of assets (including equipment and space) on a single platform. The ARCHIBUS Smart Client is a Windows application that is used for bulk data entry, data transfer, and importing and exporting data from other systems, such as Revit, into the ARCHIBUS platform. It also provides tasks for robust data analysis. The Smart Client presents data in grid views for easy access to bulk data. To exchange data with Revit, an ARCHIBUS plug-in known as ARCHIBUS Extension, provides the graphical interface between Revit and the ARCHIBUS Smart Client.

Using the ARCHIBUS Smart Client and the Extension, life-cycle parameter data captured in the Revit BIM model during the design and construction phases can flow in both directions and map directly into ARCHIBUS prior to or during commissioning and building handover.

One-way data export tools from Revit such as the COBie Data Export plugin, CTC Spreadsheet Link and Revit Reports Export process data in one direction out of Revit. With bidirectional data exchange capabilities, the ARCHIBUS Smart Client allows for automatic updating of the ARCHIBUS database. Similarly, information added or updated in ARCHIBUS platform is automatically transferred back to Revit to update the model parameters, allowing the BIM to remain up to date during the facility operation and maintenance phase.

These bidirectional workflows allow owners and facility managers to directly access and modify critical information from within Revit or ARCHIBUS, increasing flexibility and significantly reducing the level of effort required to update or edit data. Additionally, no intermediate steps are needed to transfer and link the exported data to the FM system as required by many one-way export tools.

2 Case study description

To examine the ARCHIBUS Smart Client workflow a renovation case study project was used. The project consisted of a $1.7 million (USD) HVAC, lighting, and exterior window upgrade of a 1953 Occupancy Class Group A laboratory and office building. As-built 2D drawings and project scope of work documents (submittals) were reviewed to understand the specifics of the renovation work. In total, 29 pieces of mechanical equipment in nine asset groups were included in the study. For the purpose of this paper, the asset group “Air Handler Unit” (AHU) is used as an example.

Since a Revit model was not available for this project, a basic model was created to resemble the main features of the architecture and all the mechanical components. The Revit model is shown in Figure 1. Data was identified by reviewing project documentation and then input into the model using the previously documented methods [7]. The air handler used as an example of the data flow for this paper was a make-up air handler with child assets of a supply fan, three heaters, and humidifier. The owner’s data requirements used for tracking assets are divided into common asset properties and specific asset properties are listed in Tables 1 and 2 respectively. Each asset group has its own list of attributes. Common asset properties are further broken into five groups to match with the CMMS functionality that is currently in use. Common or specific asset properties that are associated with a particular piece of equipment are identified as “instance” (I) parameters within Revit and those that are dependent on the model type are identified as “type” (T) parameters.

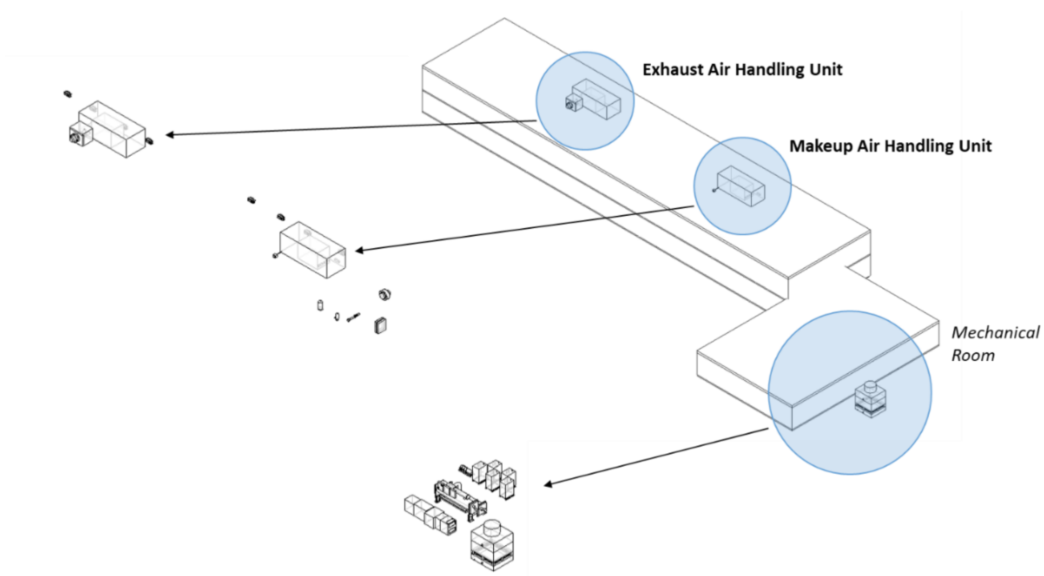

Fig. 1. Basic Revit model for the case study.

Table 1. Common Asset Properties.

Category	Label	Description	Revit
General	ASSET_TAG	Owner specified code	I
	ASSET_GROUP	AHU – Air Handler Unit	T
	DESCRIPTION	Example: MAKEUP AHU	I
	LOCATION_CODE	Example: ROOF	I
	DATE_PURCHASED	Purchase date	I
	LONG_DESC	Long description of asset	T
	LOCKOUT	Yes or no – lockout required	T
	SERIAL_NO	Serial Number	I
	MANUFACTURE_CODE	Manufacture (TRANE)	T
	MANU_PART_NUMBER	Part number by manufacture	T
	PROCEDURE_YN	Specific run procedure	T
	PARENT_ASSET_TAG	If the asset has a parent	I
	YEAR_INSTALLED		I

Parts	PART	Common maintenance parts	T
	QUANTITY	Quantity needed	T
Warranty	WARR_DESC	Warranty Included	T
	WARR_DATE_FR	Warranty coverage start	I
	WARR_DATE_TO	Warranty coverage end	I
Locations Served	LOCATION	Location equipment serves	I
	USAGE_FACTOR	% of each location served	I
Classification	CLASS_STANDARD	OmniClass & MasterFormat	T

Table 2. Specific Asset Properties – Air Handler Unit.

Asset Attribute Label	Description	Revit
BAS POINT ADDRESS	ID in Bldg. Auto. System	I
HEATING SOURCE	Example: BOILER	T
HEATING CAPACITY	Volume of air	T
TOTAL AIR FLOW	Volume of air	T
EXTERNAL STATIC PRESSURE		T
MIN. OUTSIDE AIR		T
MAX. OUTSIDE AIR		T
COOLING SOURCE	Example: Chiller	T
TOTAL COOLING CAPACITY		T
SENSIBLE COOLING CAP		T
ECONOMIZER	Yes or No (is there one)	T
ECONOMIZER TYPE		T
TOTAL STATIC PRESSURE		T
TYPE	Example: Roof Top	T

3 Data transfer using ARCHIBUS plugin and Smart Client

The overall process with a de-tailed description of the data exchange process of linking Revit to ARCHIBUS database using ARCHIBUS Extension and Smart Client Ver. 23 is summarized in Figure 2.

4 Results

This paper provided an overview for the ARCHIBUS Smart Client and Extension Ver. 23. ARCHIBUS Smart Client and Extension for Revit connect parameter information defined in Autodesk Revit with the ARCHIBUS asset management and maintenance platform. The Smart Client synchronizes data in both directions enabling owners and facility managers to modify equipment and space maintenance information in either platform, significantly improving data editing and updating workflows and reducing the level of effort required to access the information.

Several issues and lessons learned related to the ARCHIBUS Extension were observed and documented.

1. Revit Assemblies are not recognized - Elements with parent-child relationships (e.g. air handling units with fans installed in the overall assembly) were first modeled as Revit Assemblies by combining various mechanical components. This allowed the assemblies (AHU) and the components within the assembly (FAN) to have their own independent parameters. However, the ARCHIBUS Extension does not recognize assemblies as graphical elements to be mapped through the Smart Client to the ARCHIBUS platform. In addition, Revit does not allow for defining customizable parameters for different types of assemblies so they could not adequately represent the parent-child relationship required for the facility management platform. An alternative solution, though not graphically the best option, families were modeled in the same geometric space to represent both the parent and child assets. For instance, a non-descript block is used to identify the location and size of the air handling unit (AHU). This modeled object can then support the attributes and parameters associated with the AHU asset type.

2. The 'Default' dropdown is not labeled and must be changed to 'Equipment' before logging anything (Figure 3) - This process could use more clarity on what the dropdown list is, as well as how critical it is to select Equipment when cataloguing data. Possibly place this dropdown menu in a more strategic location within the plugin.

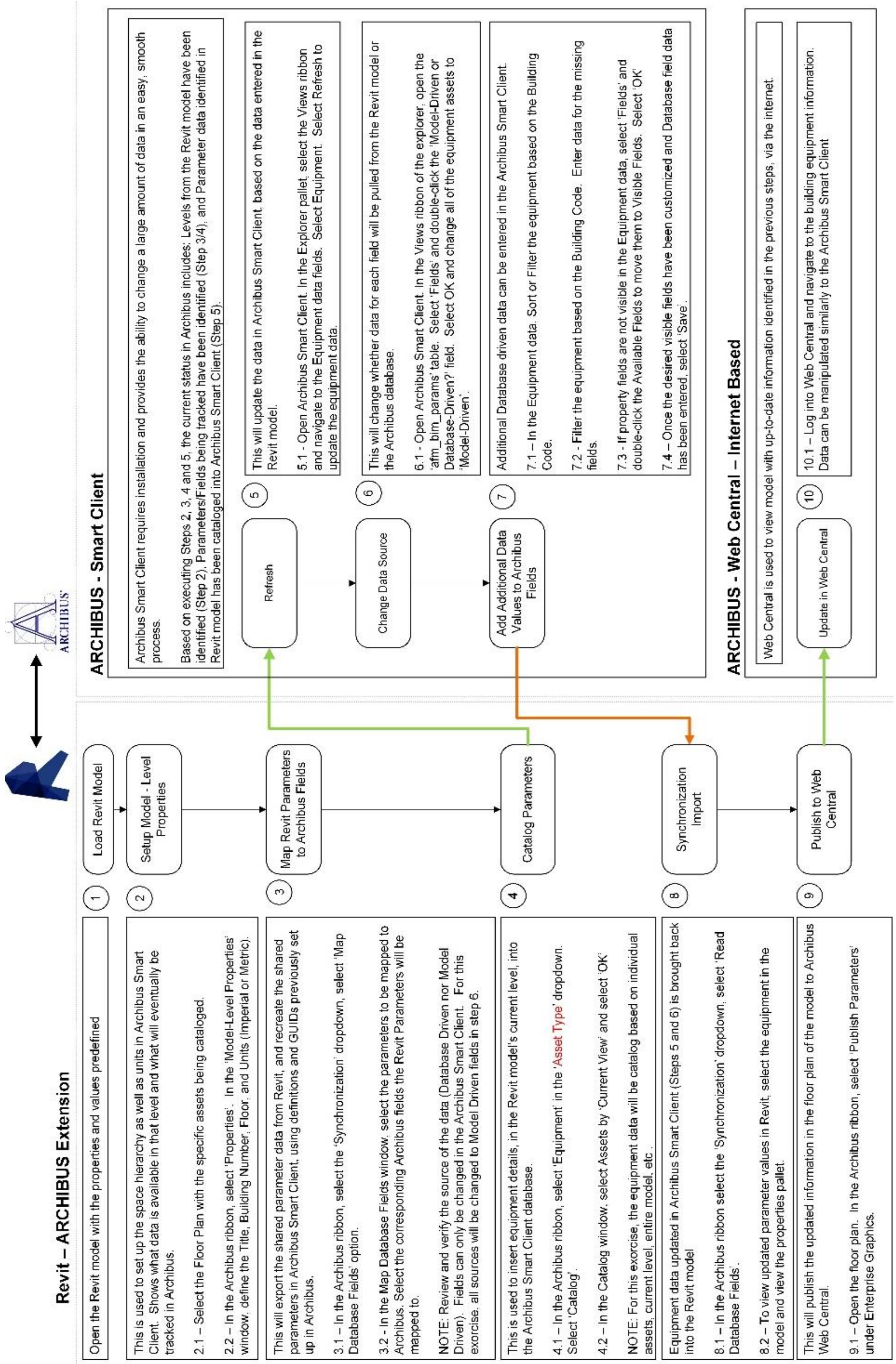

Fig. 2. Revit – ARCHIBUS data exchange process.

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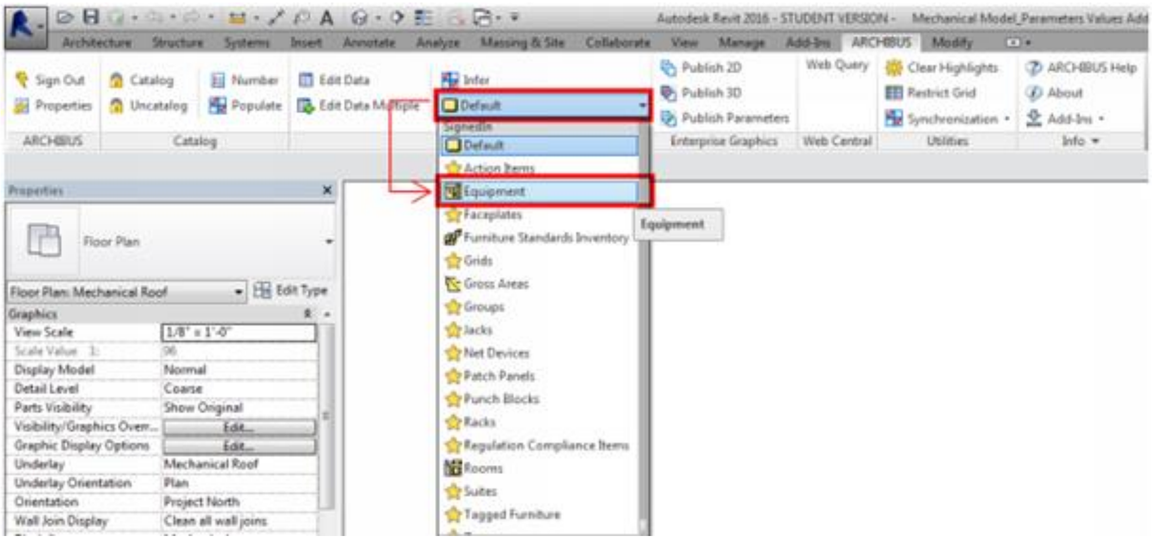

Fig. 3. Selecting Equipment in the Default Menu.

3. Cannot change the data source (Model Driven vs. Database Driven) in Revit – User must return to the Smart Client to change the data source. The Data Source allows to define the default source for the life cycle data for any asset; the Revit model or the ARCHIBUS Smart Client. The user can then map parameter fields and catalog data without having to return to the Smart Client.

4. Cannot add a new field or change an existing ARCHIBUS field – Revit parameters are mapped to ARCHIBUS fields that reside in its database. Adding new fields or editing existing fields can only be done in the Smart Client. Also adding new fields is a tedious and confusing process. To allow a user friendly process, fields should be modified within the ARCHIBUS Extension and the process should be streamlined.

5. When a change is made in the ARCHIBUS database using the Smart Client, the changes are not automatically reflected in the Revit model. Also there is no refresh button available in Revit to update the data. It is very cumbersome to go search for map database fields each time a change is made in database driven fields.

6. Naming convention for ARCHIBUS fields should be better explained – Identifying the appropriate ARCHIBUS field to map the Revit parameter to is cumbersome and unclear. It would be helpful to easily provide a formal list of current default ARCHIBUS fields with description to simplify the mapping process.

7. When creating/manipulating tables, the add fields option doesn't always display the same/all of the available fields in Smart Client. System should allow user to have access to all fields when adding fields to tables. For example: In equipment table in Smart Client, the 'Field Name' is displayed, but this is only abbreviations for the equipment fields. Example: num_serial is displayed instead of Serial Number. Add the field that would display the actual field and not the abbreviation to the available fields in the Add Field window.

5 Conclusion

The purpose of the project was to identify how a proprietary workflow of the ARCHIBUS Smart Client can be used to support data transfer needs on a pilot project into the Archibus CMMS. The pilot project involved mechanical and electrical assets that were being tracked as part of a lab building update on campus. When this was complete, lessons learned were identified on the project. A comparative analysis was also completed as to how this process related to other processes that were explored.

Overall, there are benefits to a clear bidirectional workflow that Archibus provides with a Revit plug-in that allows users to easily map Revit parameters to Archibus fields. It is easy to change and update the data extraction needed and format required. Though data export tools such as Dynamo proved to be very customizable for a system that does not have a plug-in for direct data export through Revit, it does require extensive programming when modifying the data output needs.

For the case study project looked at, the owner would be required to adopt a completely new CMMS system in order to take advantage of the Archibus plug-in which was the motivation for examining the workflows. The ultimate decision was to keep their current CMMS platform and develop a customized workflow to extract model data and import into the CMMS while working with their current platform vendor to develop a more user friendly plug-in that will not require modifying their current data and workflows to a new CMMS system.

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Micro BIM adoption in design firms: Guidelines for doing a BIM implementation plan

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Abstract

Building Information Modeling (BIM) adoption is significantly increasing and is highly supported by governmental bodies because it has great potential for the construction sector. Nevertheless, some firms do not know how to proceed for implementation. Many design firms have also already adopted BIM, so feedback is now available: several research on BIM implementation have shown that there is a lack of understanding of implementation process and a need for guidelines. Moreover, these research work, case studies and action-research have not been cross-referenced in any significant way to deduce generic and adapted guidelines for firms that are now embracing BIM implementation. In this paper, guidelines for doing a four-phases BIM implementation plan are proposed, by referencing, cross-checking, comparing, and synthetizing case studies of BIM implementation in design firms and change management literature.

Keywords: BIM; BIM implementation;micro adoption; design firms; guidelines; implementation plan; change management

1. Introduction

Building Information Modeling (BIM) adoption is increasing and is highly supported by governmental bodies because it has great potential for the construction sector. But BIM is not only a technical move, it's difficult to implement and disrupts firms' habits and practices: it is a significant organizational change. Many firms have already adopted BIM, others are much more reluctant. There are also firms who would like to implement BIM but do not have the economic opportunity to do so or do not know how to proceed [1]. Factors affecting adoption of a technology change over time as the adoption life cycle proceeds [2] : those who implement later will be more sensitive to implementation risks and more skeptical [3], it affects the implementation process [4].

Firms that implement BIM today may thus not have the same profile and motivations as those who have already done so. According to very recent surveys [5], French architects who are implementing BIM now are in "early majority" or "late majority" adopters' category. These adopters can however benefit from innovators and early adopters experience.

The purpose of this research work is to propose reliable and generic indications (guidelines) for firms that wish to implement BIM. These guidelines are based on previous case studies found in BIM-specific and change management

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literature. In a first part, outlines of research are drawn. In a second part, BIM implementation case studies are reviewed and compared to extract similarities. In a last part, guidelines for doing a four-phase implementation plan is proposed, in line with the aforementioned elements.

2. Research outlines

In this section, outlines of the research are drawn and research is positioned in relation to others in literature on three dimensions: (1) the organizational scale, (2) the adoption process stages, (3) the type of BIM knowledge content.

2.1. Organizational scale of the research: micro level

BIM is now a competitive leverage of construction sectors all around the world. For this reason, many studies and reports have compared different *counties* in their BIM adoption maturity and policies [6–9]. These studies focus on the macro level. It is also possible to provide guidelines to a *project team* for BIM implementation (meso level), or to a *firm* (micro level). These three levels have clear definitions in the context of BIM; each one has a different policy maker to whom guidelines for adoption can be addressed to (Tab. 1.).

Table 1. Granular organizational scale according to [10], and related policy makers.

Level	Definition of the level	Policy-maker
MACRO	Markets and industries	Governments, international institutions
MESO	Projects and their teams	Owner, project manager
MICRO	Organization (firm)	Top management of a firm

Regardless of project teams, integrating BIM in a firm is a radical organizational change. The micro level must therefore also be subject to guidelines for implementation but has been little studied so far. Micro-level centered studies point out that:

- There is a lack of clarity in the adoption process and it is needed to provide specific support services (guidelines, frameworks) for firms who implement BIM [11–14], specifically to SMEs [12,15].
- Firm who implement need to manage change [16,17], and review their business process strategy [15]
- There is a need of studying factors that affect implementation to be able to provide adequate guidelines [12,16,18]

This paper is micro-level centered, as it aims to provide tools for firms to manage BIM implementation.

2.2. Adoption stages covered by the research: implementation and confirmation

The adoption process is composed of 5 stages (Fig. 1.). *Implementation* (a set of activities undertaken to deploy BIM in the firm to improve specific deliverables and workflows) is only one stage of the *adoption process*, and is followed by the *confirmation stage* (when the firm evaluates if new processes are adapted and if they can keep and improve them or have to abandon them). This research covers implementation and confirmation stages of the adoption process.

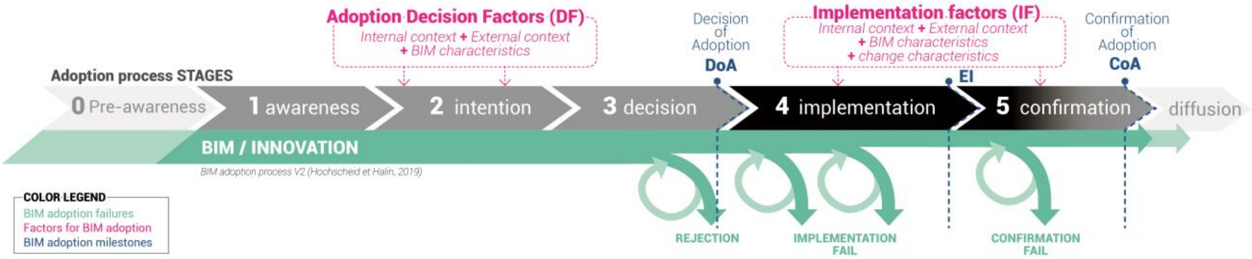

Fig.1. adoption process ([19], adapted from [3,20])

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It is needed to know what makes implementation/confirmation fail or succeed (implementation factors (Fig. 1.)) to build recommendations for firms to implement BIM [12,16,18]. Indeed, the way in which the change is implemented impacts the success of the implementation [22], hence the interest of proposing guidelines to firms. In general terms, factors that affect organizational change are: internal context, external context, characteristics of innovation, and change characteristics [19] (Fig. 1.). Yet, factors affecting implementation are rarely included on researches studying factors that affect the BIM adoption process. Very recently, a BIM adoption taxonomy which studies the impact of factors throughout the adoption process has been proposed [21] but only includes stages before DoA (Fig. 1.).

2.3. Type of BIM knowledge content proposed: guidelines for designing an implementation plan.

There are many types of documents and content whose purpose is to facilitate BIM diffusion and adoption: roadmaps, guidelines, frameworks, plans, procedures, protocols, best practice, and so on. In the BIM Knowledge Content Taxonomy (KCT) [23], these content are classified in three different categories: 1- ***Guides*** (descriptive and optional), 2- ***Protocols*** (prescriptive and optional) , 3- ***Mandates*** (prescriptive and mandatory).

Change in an organization is not easy to form exactly as intended and change management strategies are numerous [24]. The proposed solution must therefore not be formal too much and allow firms to integrate their own context and strategy. The proposal will consequently take the form of ***guidelines**** for helping top-management of firms to make their own implementation ***plan****. Guidelines for *implementing* BIM is different from guidelines for *using* it. This is similar to the distinction between *installing* software and *using* it.

- ***Guidelines*** are “a compilation of several BIM content types with the aim of providing guidance to individuals, teams or organizations” [23] (descriptive document, *guide* in the KCT)
- ***A plan*** is “a document describing activities to be performed, resources to be used and milestones to be reached within a defined timeframe” [23] (prescriptive document, *protocol* in the KCT)

3. Guidelines for BIM implementation plan: an overview

In this section, research that focused on guidelines and implementation plan for micro-level in design firms are cross-referenced to identify the main themes addressed during BIM implementation. Most of them are related to action-research and case studies. It should be mentioned that it has been difficult to collect them because of a non-homogeneous use of vocabulary in literature (*implementation* is used in lieu of *adoption* and vice-versa, and almost identical content proposals are given different names, see Appendix A). It causes Systematic Literature Review to become inoperative here. Papers have been selected throughout our work, and all concern practical BIM implementation in design firms and the organizational change that this implies. In the following sections, research have been cross-referenced on (1) aspects of change addressed, and (2) the different views and concepts raised in each study.

3.1. Overview of the aspects of change addressed

The aspects of change related to implementation addressed in literature have been listed and classified in Fig.2. into three different categories inherited from [19] :

- **Dimension of change** (“Dim.”): extent over time, within the company and the amount of change to be achieved.
- **Involvement of people in change** (“Inv.”): motivation, and people’s attitude towards change
- **Deployed solutions**: solutions, tools, deliverables and methods deployed to implement BIM.

Fig.2. shows that any change aspect is very largely covered, and no study cover all aspects. It supports the need of an overview and reliable guidelines for BIM implementation. Maybe the studies address only a few aspects at time because a few companies were included for each experimentation: deployed solutions were adapted to firms’ needs and not all solutions are relevant in all cases.

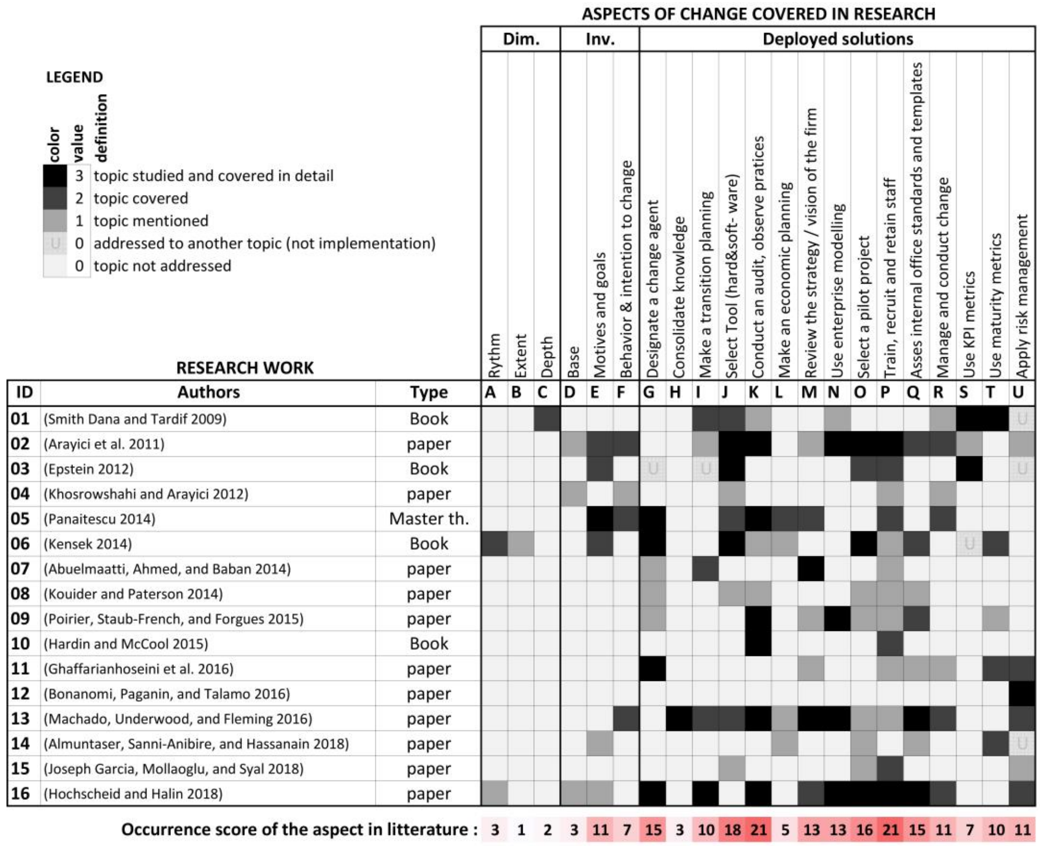

Fig.2. Cross-checking table of the aspects of change (columns) integrated in different studies (lines). See appendix A to link ID with reference. Reading note: the more an aspect is discussed in detail in a research, the darker the associated cell will be (see legend). The higher the occurrence score (OS), the more the aspect has been addressed in the literature. The OS of an aspect is calculated by adding scores of all cells in columns.

Reading the table on the columns reveals aspects that are the most covered. According to occurrence scores (Fig. 2.), aspects K, P and J are highly discussed, whereas aspects B, C, A, D and H, are very little covered. In general terms, *deployed solutions* are more covered than *dimension of change* and *people involvement*. These two categories are indeed more conceptual, but their absence of the literature may be an indicator that we currently lack a theoretical framework to grasp implementation. Another noteworthy element is that some aspects are misapplied: risk management (U, Fig. 2.) is often applied for BIM project but it is different to apply a risk-response strategy for preventing implementation failure [25]. This table can also be used to cross-reference rows and columns, to identify the reference that can give information on a particular aspect for Tab. 2.

3.2. Different views of implementation.

The selected papers show different angles of implementation and reveal various concepts of it. In this section, implementation strategies are compared to each other to extract the **concepts** inherent of implementation.

Fig. 3. shows **phases** (in grey) of the execution plan with **deliverables** for each of them (text at orange arrow tips). The main phases are: observing, planning, taking action, and anchoring change. It also shows the **iterative process** adopted for the research (blue arrows) in each phase as a validation process. In [1], this iterative process has not only been recommended for research methodology, but to run the implementation plan as a validation process. These implementation plans (Fig. 3, App B., App. C, [1]) present very similar phases, with a diagnosis, a plan, a monitoring step, and an anchoring/dissemination phases. The proposed phases can be found and have been formalized in non-BIM-specific change management literature. It is, for example, commonly admitted that “diagnosis is the basis for action in any managed change effort” [26].

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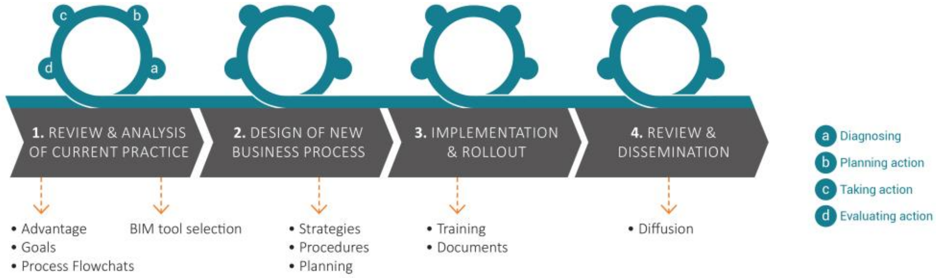
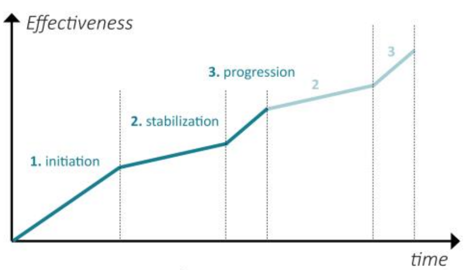


Fig. 3. Implementation plan and action-research method, adapted from [14,17]

Fig. 4. represents **effectiveness** during implementation phases and across **time**. It is a bit misleading because it doesn't reflect the loss of effectiveness that firms experience during implementation (the learning process reduces productivity), but it expresses **stabilization** and **progression** phases (**intra-firm diffusion** [27] in the other models).

Fig. 5. represents relations between different **contexts** during implementation: it addresses micro (management, BIM committee and employees), meso (project team) and macro (external context) levels. It illustrates a **continuous improvement** firms are experimenting at each new project. It refers to **operational learning** [28] and has to be linked with other levels of learning to become **organizational learning**.



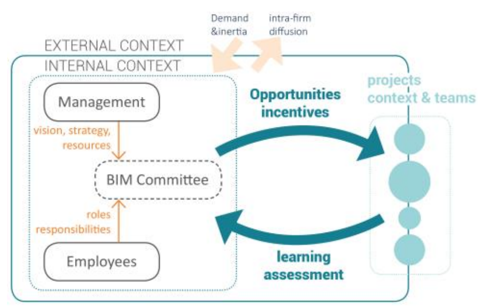


Fig. 4. (left) : Phases and effectiveness of BIM implementation [29],
Fig. 5. (right) : Embedded contexts of BIM adoption and implementation, adapted from [12].

Fig. 6. Dissects the different **components of an organization** (micro-level) to identify their interactions during implementation. According to this research, there are different path for a conventional and a collaborative technology (like BIM). BIM implementation should then begin at **operational level** according to [30] and gradually rise upwards strategical level. It may be more a question of going back and forth between these two levels for implementation. The notion of operational learning and strategic vision is therefore also present here.

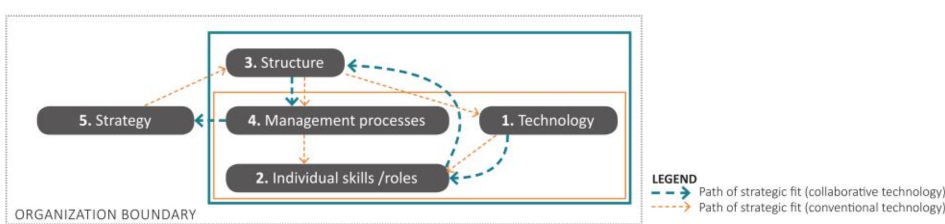


Fig. 6. Path of strategic fit during implementation of conventional and collaborative technology, adapted from [18,30].

All methods are similar in process and underline complementary concepts. The importance of analysis in organizing change is underlined and confirmed by the literature on change management. Emphasis is also placed on the importance of operational learning and continuous improvement that takes place towards the end of the process. Throughout their lives, companies alternate convergent periods (incremental change activities) and radical or discontinuous change [31,32]; the presence of both change mode is here noticeable without being really made explicit.

4. Synthesis and proposal of BIM implementation guidelines for constructing an implementation plan

Guidelines for helping firms to construct their own implementation plan are here drawn, on the basis of methods compared in section 3.2 and aspects of change studied in section 3.1. It covers the implementation stage, and the beginning of the confirmation stage of the adoption process (Fig. 7.). Transition is organized into four phases, regardless of the level of BIM to be achieved, and of the context of the firm. After an initial period of disruptive change (implementation stage (diagnosis, planning and execution phases), Fig. 7.), new uses are gradually improved and the firm switches from disruptive to progressive change (confirmation stage, anchoring phases) as seen in sect. 3.2.

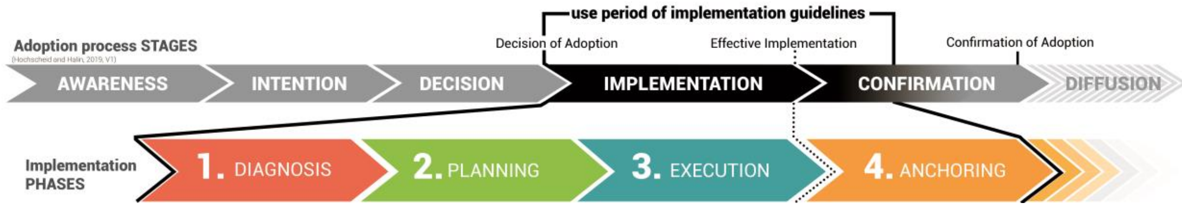


Fig. 7. The four-phases guidelines positioned on the adoption process

Each phase is detailed in two steps (Tab. 2., Fig. 8.). They are defined and connected to detailed solutions' ID (DS ID) seen above (Fig. 2.). These solutions have to be adapted to the context of firms and maturity level to achieve.

Table 2. Guidelines for implementation in design firms

Phase	Step	Definition	Outputs	DS ID
1. Diagnosis	a) observation	Carry out an audit in the firm to capture internal and external contexts, and change characteristics to identify goals, needs and motivations for implementation.	Raw information on the firm	K, T, R
	b) restitution	Present results of the audit in an understandable way using business modeling and enterprise modelling. The analysis must include risk management to anticipate implementation failure.	BPMN diagram, audit report risk management	N, R
2. Planning	a) selection	Select BIM tools, collaboration tools, BIM champions (and recruitment strategy), pilot project, type of training, internal standards to be developed. Revise vision and strategy.	A list of tasks to be performed and planned	G, H, J, M, O, R
	b) planning	Make a planning that integrates the elements defined in 2a; plan expenses (purchase of tool, training, recruitment…).	Transition calendar & economic plan	I, L, U, R
3. Executiion	a) preparation	Purchase material. Develop internal standards (templates, workflows, graphic layout…). Integrate BIM champions in this process and produce documentation on these developed standards. Training can take place at this time. Prepare KPI metrics templates.	Standards + documentation on standards	P, Q, R, S, H
	b) first tests	Carry out a first test with the BIM champions on the chosen pilot project. Use KPI metrics, report bugs to better standards.	metrics, improvements to be made	R, S, U, H
4. Anchoring	a) stabilization	Use new processes, tools and workflows on other projects. Develop an incentive policy to keep trained staff.	Retaining staff strategy	R, T, U
	b) continuous improvement	Develop new processes through use, organize a new training session, continue developing internal standards and invest new BIM uses.	Training, standards documentation	P, T, H

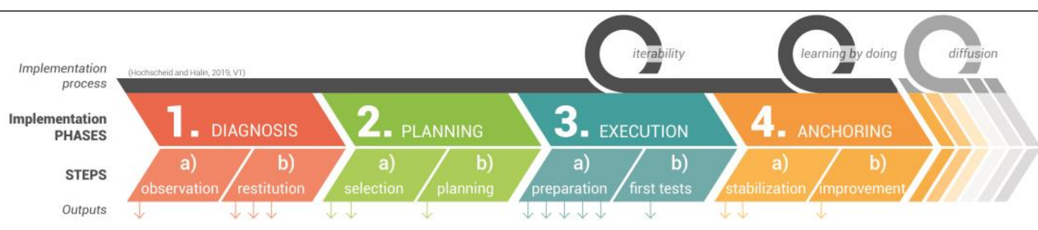


Fig. 8. Detailed process of the proposed guidelines

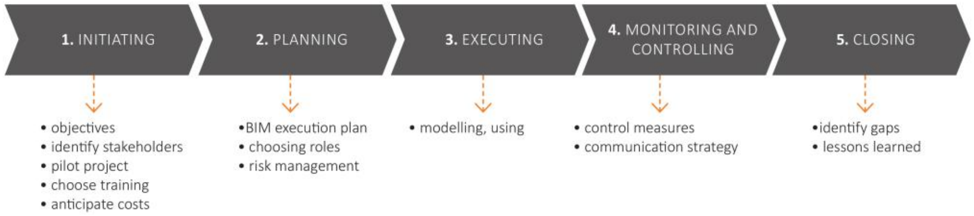
5. Conclusion

Studies that focus on BIM implementation in design firms are rare and often centered on a single case study. They generally underline the lack of clarity in the adoption process, the need for providing specific support services to firms who implement BIM and a need of studying factors that affect implementation to be able to provide these adequate tools. However, these case studies have many similarities in the way the transition is conducted, also common to change management literature. The contribution of this paper are generic guidelines extracted from the comparison of these transition approaches. But these guidelines are not sufficiently developed to be usable by firms: it is necessary to complete the comprehension we have on factors that affect implementation, to propose an adaptation of these guidelines for different firms' internal and external contexts.

Appendix A. Table 3. Various names given for BIM execution plans and guidelines.

ID	Name	Ref
01	Business Process reform	[33]
02	Iterative action research stages and process	[14,17]
03	Implementing successful Building Information Modeling	[34]
04	Roadmap for implementation	[13]
05	Structured implementation process, BIM implementation plan framework	[35]
06	Steps towards implementation	[36]
07	Path of strategic fit	[18]
08	Migration phases	[37]
09	Embedded contexts of BIM adoption / implementation contexts	[12]
10	Managing change / training BIM personnel	[38]
11	BIM implementation strategy	[15]
12	Implementation framework	[25]
13	BIM implementation approach	[16]
14	Framework for BIM implementation	[11]
15	Phases of BIM implementation	[29]
16	Implementation method	[1]

Appendix B. Implementation plan, adapted from [11]



Appendix C. Implementation plan, adapted from [16]

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Micro BIM Adoption: a Multi-Variable Analysis of Adoption within the UK Architecture Sector

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Abstract

To date a comprehensive analysis of interactions among BIM adoption factors, stages of the BIM adoption process, and time (e.g. time intervals of a national BIM initiative) is still lacking. This research aims to profile BIM adoption by mapping such interactions. The analysis is performed for the UK Architecture sector, which was represented with a sample of 177 organisations. To achieve the profiling of BIM adoption in the UK architecture sector, the study uses the outcomes from two types of inferential analysis: an ordinal logistic regression test to identify the 11 top factors influencing the BIM adoption process; and correlation analysis among the 11 top factors at different stages of the BIM adoption process (i.e. awareness, intention, and decision) and across three time intervals (i.e. pre-2011 as the time interval preceding the announcement of the UK BIM mandate, 2011-2016 as the time interval for the implementation of the UK national BIM strategy, and post-2016 as the time interval within which the mandate entered into effect).
Capturing the interactions involved in the profiling of micro BIM adoption and assimilating the outcomes in a single model unravel a further understanding of the BIM adoption process. In particular, the results reveal a dynamic behaviour characterising the micro BIM adoption process where: (1) correlated pairs of adoption factors have a varying level of influence within each adoption stage; (2) the factors involved in each pair generally change across the two dimensions (stages of adoption, and time horizon); and (4) the pairs of factors influencing adoption stages over time often combine constructs from the three clusters of drivers identified in [1] (i.e. Innovation/BIM Characteristics, External Environment Characteristics, and Organisation's Internal Environment Characteristics).

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Keywords: BIM; BIM Adoption Process; Micro BIM Adoption.

1. Introduction

Existing studies on BIM adoption in organisations (i.e., macro BIM adoption) have not significantly addressed the multi-staged nature of the adoption process and to date, our understanding of the BIM adoption process in organisations remain limited. In particular, there is a need to investigate how adoption factors, individually and jointly, contribute to process that culminate in decision to adopt BIM by organisations. This understanding is important for decision makers when developing and implementing micro BIM adoption plans. Existing studies have also used key concepts such as 'implementation', 'adoption' (either as a decision point/milestone, or a process), and 'diffusion' interchangeably [2], [3]. Potential interplays between micro BIM adoption and some market-wide coercive pressures (e.g. Government BIM mandates) over time (e.g. key time intervals of a national BIM initiative) have not been studied in detail [4]. This

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paper aims to investigate micro BIM adoption by considering these aforementioned interactions. In so doing, the paper will provide a profiling of micro BIM adoption of the UK Architecture sector.

2. Research methods and findings

The study is focussed on the first three stages of the BIM adoption process (i.e., awareness, intention, and decision) proposed by Rogers [5]. The sample of organisations involved have all adopted BIM and confirmed its use hence, this is a retrospective study. The study considers the three time intervals that underpin the UK Government BIM national initiative (i.e., pre-announcement of BIM mandate/pre-2011; trial implementation period of BIM mandate/2011-2016; and post-mandate/post-2011). To perform the profiling of BIM adoption within the UK architecture sector, the study used the following steps of data collection and data analysis:

2.1. Data collection

To attain the required data for the model, a questionnaire-based survey was sent to 509 architecture practices. 177 valid responses were returned, and 6 incomplete responses were discarded resulting in response rate of 36%. The targeted organisations were listed within the Royal Institute of British Architects (RIBA) as organisations offering BIM services. Participants (i.e. one from each organisation) were selected only if they are either knowledgeable of or were directly involved in the process of BIM adoption within their practice. The questionnaire included two sections: the first section aimed to collect demographic information (i.e. organisation size, number of BIM projects, and dates/timing of BIM adoption decision); the second section included 77 statements covering the 17 constructs. These constructs represent adoption factors organised under the three drivers (i.e., BIM Innovation characteristics; External Environment characteristics, and Internal Environment characteristics) of the Unified BIM Adoption Taxonomy published in Ahmed and Kassem [1]. A five-point Likert scale – ranging from ‘strongly disagree’ to ‘strongly agree’– was used to measure the respondents’ level of agreement with the various statements representing the measurement items/constructs as explained in the next section .

2.2. Identifying the most influencing factors on BIM adoption process

51 (i.e., 17 constructs x 3 adoption stages) hypotheses are formulated by postulating relationship effects between each of 17 factors of the driver clusters (i.e. external environment characteristics, innovation characteristics, and internal environment characteristics) and the three adoption stages (i.e., awareness, intention, and decision). Ordinal Logistic Regression analysis is employed to test the hypotheses. Not only this will help to identify the influencing factors but it will also help ranking these factors according to their influence at each stage of the BIM adoption process. The level of significance of each influencing factor is measured by comparing the P-value for the term (i.e., factor/construct) to the significance level of the null hypothesis (i.e. no association between the term and the response). The significance threshold (denoted as α or alpha) is 0.05 maximum, leaving a 5% risk of concluding that an association exists when there is not an actual association [6]. The key findings from this stage include:

- The ‘Awareness’ stage is influenced by six factors associated with the organisational internal environment characteristics and the BIM innovation characteristics. The six factors are: *Willingness, Communication behaviour, Observability, Relative advantage, Compatibility,* and *Social motivations*. No significant influence was detectable from the external environment on awareness.
- The ‘Intention’ stage is affected by nine factors (i.e., *Communication behaviour, Relative advantage, Observability, Top management support, Compatibility, Organisation size, Organisational culture, Organisational readiness,* and *Coercive pressures*) from across the three driver clusters including coercive pressure as one of the external environment drivers.

- The 'Decision' stage is influenced by seven factors (i.e., *Communication behaviour*, *Organisation size*, *Relative advantage*, *Compatibility*, *Coercive pressures*, *Organisational readiness* and *Top management support*) from across the three driver clusters.

The 11 factors, identified in this step as the most influencing factors on the BIM adoption process, will be used to perform correlation analysis in the next step.

2.3. Correlation among the most influencing factors

This section identifies the correlations between the factors affecting each stage of the BIM adoption process while considering the three time intervals (i.e., awareness, intention, and decision) and three time intervals (i.e., pre-announcement of BIM mandate/pre-2011; trial implementation period of BIM mandate/2011-2016; and post-mandate/post-2011). This analysis resulted in a set of 31 pairs of strong relationships (28 strong positive relationships and 3 negative ones) that are statistically significant (**Error! Reference source not found.**).

Table 1 The correlations among the 11 most influencing factors (31 pairs of strong relationships) on the BIM adoption process stages (time-dependent)

Stage	Time horizon	Pair of correlated factors	Correlation value
Awareness	Pre-2011	Observability ⟺ Relative advantage	(rs= .344, p=.000)
		Communication behaviour ⟺ Compatibility	(rs= .341, p=.000)
		Social motivations ⟺ Willingness	(rs= .261, p=.007)
		Communication behaviour ⟺ Observability	(rs= .246, p=.011)
		Relative advantage ⟺ Social motivations	(rs= .212, p=.029)
		Observability ⟺ Compatibility	(rs= .210, p=.031)
	2011-2016	Observability ⟺ Relative advantage	(rs= .272, p=.024)
		Relative advantage ⟺ Social motivations	(rs= .263, p=.029)
		Social motivations ⟺ Willingness	(rs= .255, p=.035)
	Post-2016	Excluded /inadequate statistically	N/A
Intention	Pre-2011	Organisational culture ⟺ Relative advantage	(rs= .491, p=.001)
		Observability ⟺ Top management support	(rs= .373, p=.013)
		Communication behaviour ⟺ Organisational readiness	(rs= .336, p=.026)
		Top management support ⟺ Coercive pressures	(rs= .334, p=.027)
		Communication behaviour ⟺ Compatibility	(rs= .300, p=.047)
	2011-2016	Observability ⟺ Relative advantage	(rs= .386, p=.000)
		Communication behaviour ⟺ Observability	(rs= .286, p=.001)
		Organisational culture ⟺ Relative advantage	(rs= .274, p=.002)
		Communication behaviour ⟺ Compatibility	(rs= .211, p=.019)
		Relative advantage ⟺ Organisational readiness	(rs= .192, p=.034)
	Post-2016	Compatibility ⟺ Coercive pressures	(rs= .911, p=.000)
Decision	Pre-2011	Communication behaviour ⟺ Relative advantage	(rs= -.424, p=.017)
		Coercive pressures ⟺ Top management support	(rs= .375, p=.038)
		Communication behaviour ⟺ Organisational readiness	(rs= .367, p=.043)
	2011-2016	Communication behaviour ⟺ Organisation size	(rs= -.189, p=.049)
		Communication behaviour ⟺ Compatibility	(rs= .302, p=.001)
		Communication behaviour ⟺ Relative advantage	(rs= .243, p=.011)
		Relative advantage ⟺ Organisational readiness	(rs= .210, p=.029)
	Post-2016	Relative advantage ⟺ Organisational readiness	(rs= .414, p=.011)
		Compatibility ⟺ Top management support	(rs= .355, p=.031)
		Relative advantage ⟺ Compatibility	(rs= .348, p=.035)
		Coercive pressures ⟺ Organisational readiness	(rs= -.352, p=.033)

⟺ strong positive relationship ⟺ strong negative relationship

These results are visualised in Figure 1 using a two-dimensional model, with one dimension being the stages of the BIM adoption process and the other dimension being the time-horizon, with the following conventions:

- The pairs of factors influencing awareness were top-to-bottom (A to F) arranged according to their actual power of influence. For example, in **Error! Reference source not found.** the first block of the 'Awareness stage' in the Pre-

2011 period ranks the following pairs from top-to-bottom in a descending order: [i.e. Observability ⇔ Relative advantage (rs= .344, p=.000); Communication behaviour ⇔ Compatibility (rs= .341, p=.000); Social motivations ⇔ Willingness (rs= .261, p=.007); Communication behaviour ⇔ Observability (rs= .246, p=.011); Social motivations ⇔ Relative advantage (rs= .212, p=.029); and Observability ⇔ Compatibility (rs= .210, p=.031)].

- The level of influence of each pair is symbolised using simple pie diagrams: 1 full circle for p-values between p=0.000 – p=0.009; ¾ circle for p-values between p=0.01 – p=0.025; ½ circle for p-values between p=0.026 – p=0.04; and ¼ circle for p-values between p=0.041 – p=0.05.

Three colour codes are used to identify the factors appurtenance to the three driver clusters. Pink, orange, and blue are used for the External Environment Characteristics, Innovation/BIM Characteristics, and Organisation's Internal Environment Characteristics, respectively.

The profiling of micro BIM adoption with the model (Figure 1) presents an integrated view of the adoption problem by addressing the interactions between: pairs of correlated adoption factors, stages of the BIM adoption process, and the time horizon. The model shows that micro BIM adoption is characterised by a dynamic behaviour where:

- Correlated pairs of factors exert a varying level of influence within each adoption stage and across different stages and time horizons. For example, the pair "Communication behaviour ⇔ Compatibility" has a continuous influence with its effect transferring (a) across three consecutive stages within two periodical time-horizon (i.e., from 'Awareness' to 'Intention' in Pre-2011, then from 'Intention' to 'Decision' in 2011-2016), and (b) across two consecutive periodical time-horizon of the same stage (i.e., from Pre-2011 to 2011-2016 at 'Intention'). Hence, this pair plays a role in driving the organisation to: gain knowledge about the innovation (i.e. formulate awareness); develop a favourable attitude (i.e., Intention) towards BIM adoption; and move towards formulating the decision to adopt BIM;
- Factors involved in each correlated pair influence BIM adoption generally change across the adoption stages and the time horizon. For example, the pairs (Relative advantage ⇔ Observability), (Communication behaviour ⇔ Compatibility), and (Relative advantage ⇔ Organisational readiness) all change the composition of the pair involved in exerting influence on the BIM adoption process; and
- Pairs of factors influencing adoption stages over time often combine constructs from the three clusters of drivers (i.e. Innovation/BIM Characteristics, External Environment Characteristics, and Organisation's Internal Environment Characteristics). This indicates that micro BIM adoption is a dynamics system whose understanding require the simultaneous contemplation of these three environments.

These findings, by revealing the different types of interactions between the factors affecting the BIM adoption process across two important dimensions (i.e. stages of the BIM adoption process stages, and time) improve the understanding of the micro BIM adoption. And by so doing, it could inform micro BIM adoption implementation plans. For example, in the case of Pair B (i.e. communication behaviour and compatibility) influencing the awareness stage at pre-2011, a decision maker may implement activities that change the communication behaviour (i.e. the degree of openness and engagement of an organisation with social groupings and networks interested in innovation adoption and promotion) of an organisation to make the organisation perceives the innovation as more compatible with their previous experiences and current needs and values. Further, in organisations where readiness was achieved between [2011 - 2016] other pairs of correlated factors are involved, and none of these pairs entails factors from Pair B (communication behaviour and compatibility). By interpreting the model's results in this way, decision makers may be able to calibrate and tailor micro BIM adoption activities to their special circumstances depending on their position across both the adoption and time dimensions.

3. Conclusion

This paper performed the profiling of micro BIM adoption within the UK architecture sector. The profiling of micro BIM adoption captured interactions between adoption factors, BIM adoption stages, and time. The time dimension was split into three time intervals denoting key phases of the UK national BIM initiative. The profiling of BIM adoption was achieved from two different sets of results: (1) 11 top influencing factors with positive and significant influence on the BIM adoption stages identified from the Ordinal Logistic Regression;; and (2) correlation analysis among the 11 factors at different stages of the BIM adoption process and at different time intervals, which resulted in a set of 31 pairs of strong relationships (28 strong positive relationships and 3 negative ones). These two set of results were used to build a model which provided an integrated view of micro BIM adoption by capturing the interactions between pairs of correlated factors, the BIM adoption process, and time. The model was used to show some of the dynamic patterns inherent in micro BIM adoption. The model introduced a new '*dynamic'* view of micro BIM adoption where the potential influence, the level of the influence, and the factors exerting the influence vary according to both the stage of the BIM adoption process, and time. In future, the work will be extended to include organisation size (i.e. micro, small, medium, and large) as an additional variable involved in this dynamic view of micro BIM adoption.

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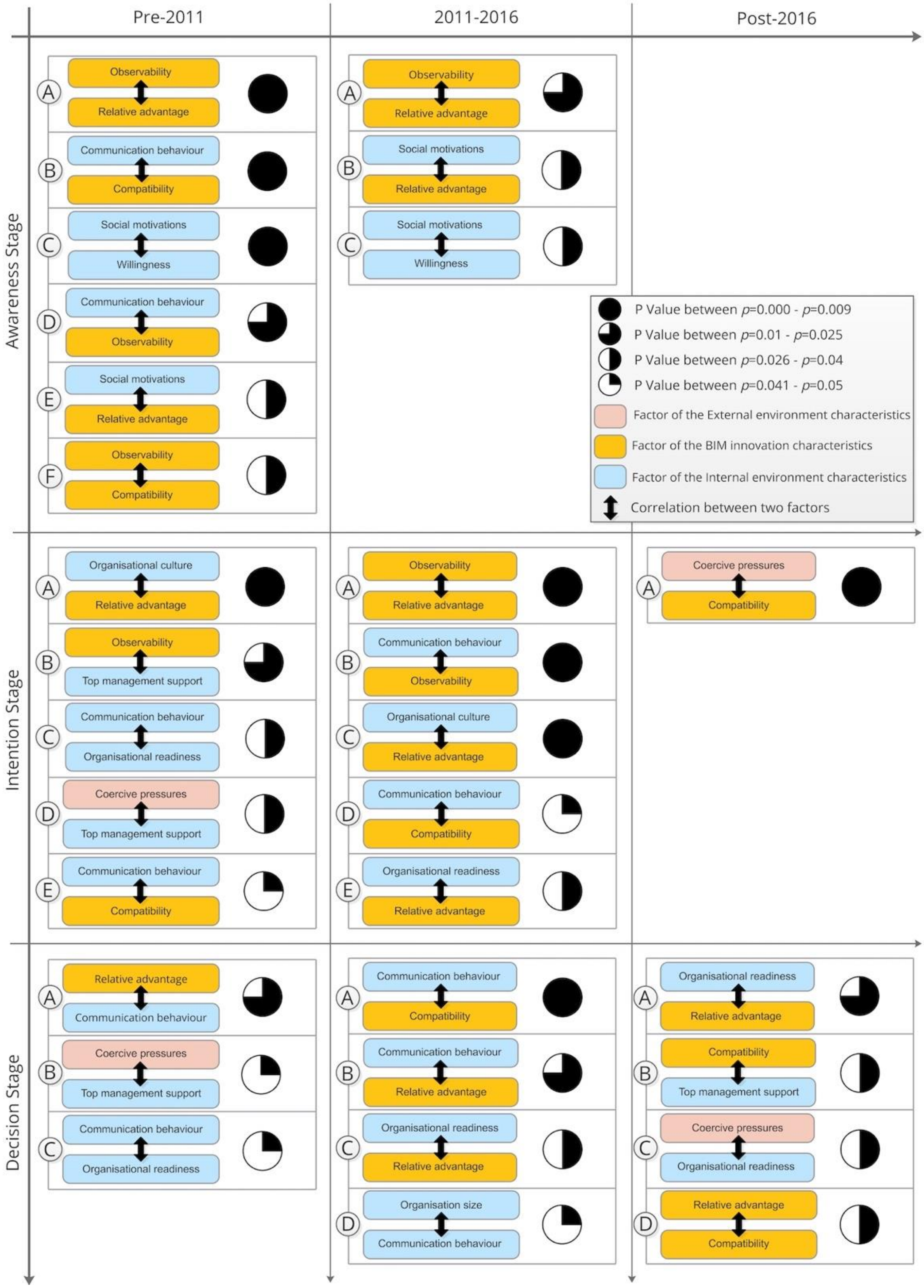

Figure 1 A two-dimensional model profiling BIM adoption process in UK Architecture Sector

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Micro BIM Adoption: Identifying Cause and Effect Factors and Analysing their Inter-dependencies using a Fuzzy DEMATEL Approach

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Abstract

Several factors affect the process of BIM adoption within organisations (i.e. micro BIM adoption). An extensive collection of such factors were included in a unified BIM adoption taxonomy published in Ahmed and Kassem (2018). These factors are distributed across three areas of adoption drivers: the characteristics of the innovation itself (i.e., BIM), the external environment, and the internal environment of the adopting organisation. BIM adoption is a multi-staged process that entails varying interactions between factors from across the three driver areas and the stages of the BIM adoption process. Hence, this study argues for an improved understanding of the adoption topic beyond the current level offered by common approaches such as ranking factors affecting adoption (conceived as a single decision/milestone) and analysing correlations. In particular, there is a need to analyse the complex inter-dependencies between factors affecting the adoption process and its individual stages (i.e., awareness, intention, decision, etc.). This paper aims to understand these inter-dependencies by considering the micro BIM adoption as a complex system. The paper investigates the relative levels of influence between the factors affecting the system and classifies such factors in cause and effect factors at different stages of the adoption process. To achieve this objective, the research employs the Fuzzy Decision Making Trial and Evaluation Laboratory (F-DEMATEL) method. The application of the F-DEMATEL considered the top 11 factors (as identified in Ahmed and Kassem, 2018) that affect BIM adoption within the UK Architecture sector. The F-DEMATEL was applied for the entire adoption process as a 'single' system (i.e. without separating it into multiple stages) and for each individual stage (i.e. awareness, intention, and decision). The results from the F-DEMATEL (i.e., classification of factors into cause and effect groups and into four quadrants, and their inter-relationships) provided a new understanding of the BIM adoptions process. These results can be used to tailor and prioritise BIM implementation actions and investments when develop micro BIM adoption strategies.

Keywords: BIM; BIM Adoption Process; Micro BIM Adoption; F-DEMATEL; Adoption Factors

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1. Introduction

Building Information Modelling (BIM) connotations have significantly increased over time and is now considered as the current expression of digital innovation within the construction sector (Succar and Kassem, 2015). The disruptive nature of BIM as an innovation is manifested across three clusters of the organisational scale: Macro, Meso and Micro. At the Macro level, BIM is attracting the attention of market-wide players such as major public and private sector procurers and suppliers, and regional and national authorities (Kassem and Succar, 2017). The effect of BIM at the Macro scale is also exemplified by the emergence of maturity models for measuring market-wide maturity (as in Kassem and Succar, 2017), and the significant effort by many regional and national public authorities to promote BIM adoption through the launch and implementation of national BIM initiatives. At the Meso scale, BIM disruption is evident by the need to: change the conventional inter-organisational relationships and adapt procurement systems for BIM-enabled project (Hatem, 2008, McAdam, 2010, Papadonikolaki, 2017); share risks and rewards by project participants (Ghassemi and Becerik-Gerber, 2011); improve technical interoperability and communication among the project participants (Ghassemi and Becerik-Gerber, 2011). At the Micro scale, BIM is bringing a new set of processes, technologies and policies (Succar, 2009). Studies to understand BIM adoption have been scattered across these three levels. However, the key limitations in most of the existing studies include: the contemplation of 'adoption' as a milestone or a decision instead of a multi-staged process; the accounting for a limited number of factors affecting adoption; the unclear delineation between related concepts such as 'adoption', 'implementation', and 'diffusion'; and the limitations of investigations to aspects such as ranking factors affecting adoption and analysing their correlations. This study builds up on previous work that identified an extensive array of adoption factors as part of a unified BIM adoption taxonomy and calculated their levels of influence on the first three stages of the BIM adoption process (i.e. awareness, intention, and decision) (Ahmed and Kassem, 2018) by classifying the factors into cause and effect groups and analysing their interdependencies. To this end, this study employs the Fuzzy Decision Making Trial and Evaluation Laboratory (F-DEMATEL) method by considering the 11 top factors that influence the BIM adoption process. The next two section will present the F-DEMATEL method and the findings, respectively. The final section will discuss and conclude.

2. Methodology and research methods

The top 11 factors, identified in Ahmed and Kassem (2018), as top influencing factors on the BIM adoption process are used in this study. These factors are: Willingness to adopt BIM (F1), Communication behaviour of an organisation (F2), Observability of BIM benefits (F3), Compatibility of BIM (F4), Social motivations among organisation's members (F5), Relative advantage of BIM (F6), Organisational culture (F7), Top management support (F8), Organisational readiness (F9), Coercive pressures (Governmental mandate, informal mandate) (F10), and Organisation size (F11). The F-DEMATEL, which is an expanded approach from the DEMATEL method, is used to classify these factors into cause and effects group and to analyse their potential inter-dependencies while influencing the adoption process.

The decision-making trial and evaluation laboratory (DEMATEL) approach is a technique for constructing and analysing a structural model for investigating the impact of causal relationships amongst an array of interacting factors (Wu and Lee, 2007). DEMATEL aims at directly comparing the interdependency relationship among elements, attributes, and criteria of a system and utilising matrices to analyse the direct and indirect causal relationships and impact level among elements. These relationships are envisaged exploiting the 'graphical structural matrices' and 'causal diagrams' (i.e., digraphs) to interpret and verify the contextual causal relationships and impact level among the elements in the complex system and support in decision-making (Lee et al., 2010). Hence, DEMATEL can transform a complex system into a clear causal relationship with a well-defined structural model. Simplifying the interactions among elements in the complex system into a justified cause and effect relationship via the interaction impact level among quantified elements assists in discovering the central problem in the complex system and improving direction (Wu and Lee, 2007).

In many industries, numerous business organisations rely on 'group decision-making' to locate an agreeable resolution in actual decision-making problems. However, in decision-making problem associated with complex systems, the assessment presented by decision-makers or experts on subjective principles of a specific item is constantly communicated in linguistic expressions rather than crisp values, depending on expertise and knowledge (Lin, 2013). To address potential inaccuracies when formulating decisions, fuzzy set theory is used to quantify vague perceptions involved in judgments (Wu and Lee, 2007). Arithmetically, every number in the fuzzy set between 0 and 1 denotes a fractional fact, while crisp sets conform to 0 or 1 binary logic (Wu and Lee, 2007, Lin, 2013).

The fuzzy linguistic process involves transforming linguistic wording into fuzzy numbers after which de-fuzzifying these fuzzy numbers is applied to obtain accurate values (Tsaur and Kuo, 2011, Lee et al., 2014) (Table 1). The defuzzification solution implemented in the current study utilises the minimum and maximum fuzzy number to define the left and right edge values respectively. The total integral value is calculated based on the weighted average of the membership function. Determining the crisp values of the fuzzy set numbers $\tilde{A}$ are described in the steps below using the triangular fuzzy numbers $\tilde{N}$ method (Chang et al., 2011, Lee et al., 2014):

Table 1 The triangular fuzzy linguistic scale set

Linguistic terms/influence	Score	Triangular Fuzzy Number
No influence	0	(0, 0, 0.25)
Very low influence	1	(0, 0, 0.25)
Low influence	2	(0.25, 0.50, 0.75)
High influence	3	(0.50, 0.75, 1.00)
Very high influence	4	(0.75, 1.00, 1.00)

A structured questionnaire survey was used to collect the data required for the F-DEMATEL method in order to identify and analyse the potential interdependencies among the factors that influence the process of BIM adoption. The questionnaire included two sections. The first section aimed to obtain the respondents' level of agreement with 110 statements signifying pair-wise relationships between each pair of potentially interacting factors (i.e. 11 factors x 10 relationships) using a five-point Likert scale. The definitions (Table 2) of the most influencing factors on the BIM process were presented to the respondents in the introductory part of the questionnaire. The second section of the questionnaire was intended to capture demographic information (e.g., gender, job title, and age) to verify the responses from selected and invited respondents. The respondents required to be knowledgeable about the process of BIM adoption within organisations as either internal or external change agents. 12 valid responses were returned and two incomplete responses were discarded.

Table 2 Definitions of the most influencing factors/ evaluation criteria of the F-DEMATEL Questionnaire

Factors	**Definitions**
Willingness to adopt BIM (F1)	Refers to the favourable or unfavourable attitude of organisation or a decision-making unit towards the innovation/ BIM.
Communication behaviour of an organisation (F2)	The degree of openness and engagement of an organisation with social groupings and networks interested in innovation adoption and promotion.
Observability of BIM benefits (F3)	The degree to which the results from innovation/BIM adoption are visible and tangible.
Compatibility of BIM (F4)	The degree to which an innovation/BIM aligns with potential adopter's previous experiences and current needs and values.
Social motivations among organisation's members (F5)	The motivation to engage in behaviours that benefit others such as considering others' perspectives, stimulating knowledge exchange, and focusing on collective goals.
Relative advantage of BIM (F6)	The degree to which an innovation/BIM is perceived as being better than the system/practice it replaces.
Organisational culture (F7)	The shared norms, beliefs, principles, and traditions - held by the members of an organisational practice – which contribute to the members' understanding of the organisational functioning.
Top management support (F8)	The degree to which senior management understands the importance of the innovation/BIM function and the extent to which they are involved into promoting the system adoption.

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Organisational readiness (F9)	The extent to which organisational members are psychologically and behaviourally prepared to implement a change, their mutual determination to perform the change, and their mutual faith in their aggregate capacity to achieve the change.
Coercive pressures (Governmental mandate, informal	The formal and informal forces applied to organisations by other organisations (public and private clients/employers, etc.).
Organisation size (F11)	The total number of full-time members of staff of an organisation (e.g., micro, small, medium, and large).

The F-DEMATEL method was applied according to the following steps:

- **Step 1:** Identify the criteria's influential factors/elements within the complicated system under investigation, and a measurement scale to determine the direction and the degree of influence of the relationships among the elements of the criteria. Then, pairwise relationships are established based on the views and experience of the experts/respondents. The comparison scale may comprise five level of influences (See Table 1).

- **Step 2:** Formulate the initial direct-influence matrix ***K***, which is an $n \times n$ matrix, determined from the pairwise comparisons of the influences and the directions among the criteria's factors. $K = [k_{ij}]_{n \times n}$, where k_{ij} is the level of influence that criterion i exerts on criterion j (Equation 1).

$$K = \begin{pmatrix} 0 & k_{12} & \cdots & k_{1n} \\ k_{21} & 0 & \cdots & k_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ k_{n1} & k_{n2} & \cdots & 0 \end{pmatrix} \tag{1}$$

- **Step 3:** Calculate a normalised direct relation matrix ***N*** using Equations 2 and 3, where all main diagonal elements are equal to zero.

$$\lambda = \frac{1}{Max_{1 \le i \le n}\left(\sum_{j=1}^{n} k_{ij}\right)} \quad , \quad i, j \in \{1,2,...,n\} \tag{2}$$

$$N = \lambda \times K \tag{3}$$

- **Step 4:** Calculate the total relation/impact matrix ***T*** using Equation 4, where ***I*** is the identity matrix.

$$T = N(I - N)^{-1} \tag{4}$$

- **Step 5:** Calculate the crisp values using Equation 5

$$k_j^{crisp} = \left[k_j^{ls}\left(1 - k_j^{ls}\right) + kps_{ij}^{n} \times kps_{ij}^{n}\right] / \left[1 - k_j^{ls} + k_j^{ps}\right] \tag{5}$$

- **Step 6:** Calculate the sum of the values of each row ***D*** and each column ***R*** separately of the total relation matrix, D_i and R_j denote the sum of rows (i.e., direct influences) and columns (i.e., indirect influences) respectively, using Equations 6, 7, and 8.

$$T = \left[t_{ij} \right]_{n \times n} \quad , \quad i, j \in \{1,2,...,n\} \tag{6}$$

$$D_i = \left[\sum_{i=1}^{n} t_{ij} \right]_{1 \times n} \quad , \quad i, j \in \{1,2,...,n\} \tag{7}$$

$$R_J = \left[\sum_{J=1}^{n} t_{ij} \right]_{1 \times n} \quad , \quad i, j \in \{1,2,...,n\} \tag{8}$$

- **Step 7:** Visualise the DEMATEL cause and effect digraph by plotting the dataset of (***D+R, D-R***). (***D+R***) represents the total 'Importance' level of each criterion/factor whereas (***D-R***) denotes the 'Relation' and helps to categorise the criteria into cause-and-effect groups. When the (***D-R***) is positive, the criterion belongs to the 'cause group', otherwise, it belongs to the 'effect group'.

3. The F-DEMATEL model of the whole system of BIM adoption process (11 factors/ time-independent)

In the causal diagram (or also called 'Impact-digraph Map' of the 11 criteria) (Figure 1a), the values of (D+R) and (D-R) are represented by the horizontal axis and the vertical axis, respectively. The (D+R) value determines the degree of significance of the factor on the process of BIM adoption. The (D-R) value categorises the factors into cause group and effect group. The results have revealed two groups of factors (Table 3 and Table 4): *cause group (influencing factors)* with high centrality degree and positive causal degree; and *effect group (affected factors)* with high centrality degree and negative causal degree, which are interdependent. In a descending order of their average influence , the cause group's factors are: Organisation size (F11), Coercive pressures (Governmental mandate, informal mandate) (F10), Relative advantage of BIM (F6), Observability of BIM benefits (F3), Compatibility of BIM (F4), and Organisational readiness (F9). The effect group's factors are Willingness to adopt BIM (F1), Top management support (F8), Communication behaviour of an organisation (F2), Social motivations among organisation's members (F5), and Organisational culture (F7). The cause factors have an influence on the whole system, and the effect factors tend to be easily influenced by the other factors. The causal diagram can be further divided into four quadrants (Figure 1b):

- Quadrant I: It contains the 'Core' factors with high prominence and high relation. These are *Relative advantage of BIM* (F6), *Observability of BIM benefits* (F3), and *Organisational readiness* (F9). These cause factors influence most of the effect factors in Quadrant IV and their resolutions contribute to unlock many factors within the system. Hence, these factors should be prioritised and addressed first in a BIM adoption strategy.

- Quadrant II: Includes the 'Driving' factors - or also called autonomous givers - with low prominence and high relation. These factors are *Organisation size* (F11), *Coercive pressures* (F10), and *Compatibility of BIM* (F4). These factors are somewhat independent (e.g. cannot be influenced easily) but they have influence on many other factors within the system (i.e., effect factors in Quadrant IV).

- Quadrant III: It contains independent factors or autonomous receivers. It includes only one factor, *Organisational culture* (F7), which is relatively an independent factor due to its low prominence and low relation. It can either be individually solved or may be influenced only by a few other factors within the system (i.e., F1 and F8 of effect Quadrant IV).

- Quadrant IV: Includes the 'effect' factors with high prominence and low relation. This quadrant comprises of four factors; *Willingness to adopt BIM* (F1), *Top management support* (F8), *Communication behaviour of an* *organisation* (F2), *and Social motivations among organisation's members* (F5). These factors are influenced by other factors and represent a core cluster that must be managed. However, they cannot be addressed directly. This cluster include F1 (*Willingness to adopt BIM*) which has the highest influence.

Table 3 The De-Fuzzified total relation matrix T of the whole system of BIM adoption process (11 factors)

Factors	F1	F2	F3	F4	F5	F6	F7	F8	F9	F10	F11
F1. Willingness	0	0.061	0.050	0.045	0.054	0.047	0.061	0.059	0.056	0.042	0.031
F2. Communication behaviour	0.071	0	0.064	0.060	0.063	0.059	0.058	0.061	0.063	0.044	0.027
F3. Observability of BIM	0.073	0.064	0	0.063	0.060	0.065	0.050	0.078	0.050	0.042	0.029
F4. Compatibility of BIM	0.068	0.057	0.057	0	0.061	0.056	0.050	0.069	0.051	0.042	0.029
F5. Social motivations	0.074	0.070	0.050	0.047	0	0.056	0.056	0.061	0.049	0.038	0.029
F6. Relative advantage of BIM	0.077	0.073	0.065	0.069	0.058	0	0.055	0.074	0.057	0.044	0.030
F7. Organisational culture	0.073	0.065	0.046	0.043	0.065	0.056	0	0.066	0.058	0.043	0.028
F8. Top management support	0.074	0.069	0.051	0.043	0.053	0.045	0.059	0	0.061	0.043	0.035
F9. Organisational readiness	0.071	0.065	0.057	0.052	0.059	0.066	0.051	0.065	0	0.042	0.032
F10. Coercive pressures	0.074	0.066	0.047	0.044	0.059	0.052	0.058	0.079	0.058	0	0.036
F11. Organisation size	0.064	0.064	0.050	0.047	0.057	0.044	0.057	0.059	0.049	0.043	0

Table 4 The F-DEMATEL results of the whole system of BIM adoption process (11 factors)

Factors	D	R	Defuzzified (D+R)	Rank	Defuzzified (D-R)	Cause/Effect
F1. Willingness	0.529	0.743	1.272	11	-0.214	Effect
F2. Communication behaviour	0.594	0.678	1.272	3	-0.084	Effect
F3. Observability of BIM	0.597	0.559	1.156	2	0.038	Cause
F4. Compatibility of BIM	0.563	0.535	1.099	7	0.028	Cause
F5. Social motivations	0.554	0.611	1.164	9	-0.057	Effect
F6. Relative advantage of BIM	0.626	0.569	1.195	1	0.056	Cause
F7. Organisational culture	0.565	0.576	1.141	6	-0.011	Effect
F8. Top management support	0.555	0.694	1.249	8	-0.139	Effect
F9. Organisational readiness	0.582	0.576	1.158	5	0.006	Cause
F10. Coercive pressures	0.592	0.444	1.036	4	0.149	Cause
F11. Organisation size	0.553	0.325	0.878	10	0.228	Cause

a **b**

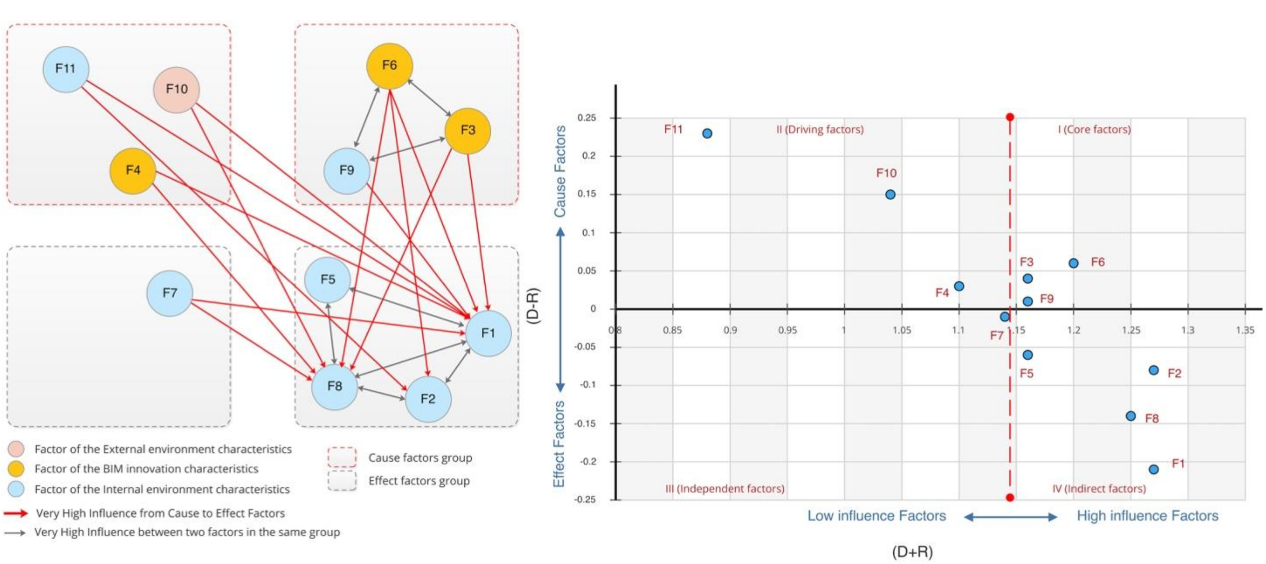

Figure 1 (a) Impact Relation Map depicts the cause and effect relationships and interdependencies among the most influencing factors affecting the process of BIM adoption; (b) Causal diagram (Digraph) of the interdependent cause and effect relationships among the most influencing factors

4. Findings and Conclusions

Together the three factors in the first quadrant (F6, F3, and F9) and second quadrant (F11, F10, and F4) that represent the core factors and the driving factors affect the four factors of the fourth quadrant (F1, F8, F2, and F5). Thus, this suggests that to address the effect group factors in the BIM adoption process, it is necessary to first target the core factors and the driving factors that must be given more attention by decision makers within the adopting organisations. This means that implementation actions aimed at addressing BIM characteristics [i.e., *Relative advantage* (F6), *Observability* (F3), and Compatibility of BIM (F4)] may simultaneously contribute to fulfil some of the internal environment characteristics [i.e., *Organisational readiness* (F9), Organisational culture (F7), *Social motivations among organisation's members* (F5), *Communication behaviour of an organisation* (F2), *Top management support* (F8), and *Willingness to adopt BIM* (F1)]. This involves, for example, implementation actions to reinforce the perceived benefits obtained from adopting BIM (F6), which may contribute to increase the openness and engagement of the potential adopters with social groupings and networks interested in BIM adoption and promotion (F2); stimulate more willingness to adopt BIM (F1); and invite more executive support (F8) to facilitate the BIM adoption process. Similarly, demonstrating visible and tangible results of successful BIM adoption examples of other organisations (F3), and clarifying how BIM could be aligned with the adopter's previous experiences and current needs and values (F4), may also affect *Top management support* (F8) and *Willingness to adopt BIM* (F1)].

Combining the shared norms, beliefs, and traditions (F7), held by the members of an organisational practice, with *Organisational readiness* may contribute to stimulate *Willingness to adopt BIM* (F1). Consequently, strengthening the BIM innovation characteristics (F6, F3, and F4) together with organisational characteristics (F9, F7, F5, F2, and F1) may invite more executive support in the organisations [i.e., *Top management support* (F8)].

A BIM mandate [i.e., *Coercive pressures (Governmental mandate, informal mandate)* (F10)], as an independent factor, exert influence on two other factors only, the executive support in organisations (F8) and the willingness to adopt BIM (F1), both of which are affected by most of the other core factors involved in the system.. Therefore, potential mandatory BIM requirements (e.g. market-wide mandate by government or ad-hoc mandates by specific appointing parties) may have an influence on BIM adoption and diffusion across the industry although this was not identified as one of the most prominent factors driving adoption and diffusion. .

Organisation size (F11) was identified as an independent mostly influencing Willingness to adopt BIM (F1) and Communication behaviour of an organisation (F2) . This means that the level of influence exerted by the various factors influencing involved in the system may vary according to the different sizes of organisations (i.e., micro, small, medium, and large). To understand these potential relationships, further analysis such as the application of the F-DEMATEL approach on organisations of different sizes is required.

The results from the F-DEMATEL (i.e., classification of factors into cause and effect groups and into four quadrants, and their inter-relationships) provided a new understanding of the BIM adoptions process. These results can be used to tailor and prioritise BIM implementation actions and investments when develop micro BIM adoption strategies. Factors classified as Core factor (Quadrant 1) should receive most of the attention and investment as their resolutions will subsequently unlock most of the other factors within the adoption system. However, the presence of pairs of such factors within the environment of the adopting environment may trigger new dynamics. Hence, a further understanding of the adoption problem is required. To address this need in future work, the authors will combine the results from the DEMATEL with those from the correlation analysis to develop systems thinking models for the micro BIM adoption problem.

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On-site quality assurance: moving from forms to digital capture

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Abstract

The construction industry is in the midst of a transition with traditional design systems being replaced by novel 3D modelling technologies. This transition takes place gradually rather than radically, and while new systems (e.g. Building Information Modelling, BIM) become increasingly diffused in the industry, many legacy systems and practices are left intact. Quality assurance using the old method of filling out forms for the registration of errors and omissions is replaced by systems such as RIB Capture, where an app on a mobile phone is used to take a photo which is immediately sent to the person involved, e. g. carpenter, plumber, electrician etc. We ran a case study in a large industry standard type of residential project executed by a contractor. Data were collected based on a series of qualitative interviews conducted with the on-site personnel. This was analyzed according to the Technology Acceptance Model, which explains how individuals develop an intention to use new technology. Our contribution to the body of literature is that we compare the technology acceptance of new and existing quality assurance methods in order to unearth their relative advantages. This work is important for managers deciding on a combination of quality control tools, enabling them to better run their projects efficiently.

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Keywords: RIB Capture, Construction Management, Technology Acceptance Model, Quality assurance.

1. Introduction

Quality assurance is, in construction as in other fields, a central goal for all deliverances. Quality can be understood as a condition free of deficiencies [1]. According to several studies, most building defects originate during production or construction [2], and they are costly – accounting for approximately 15 % of the total construction costs [3]. While prevention would be preferable, it is not always possible or even the most cost-effective [4], so there will always be a need for appraisal and correction of failure.

Digitization, headed by Building Information Modelling (BIM), has taken over as the preferred method for anything from design collaboration to scheduling, cost planning, and facility management; improving efficiency and quality along the whole chain [5]. Digital tools are not reserved for designers and consultants at their desks, as on-site workers are also embracing the technology with access to the 3D model on mobile devices. Along with this development, numerous associated mobile apps are made available for the construction phase, offering tools for anything from model viewing and safety monitoring [6] to note taking, invoicing and form filling – the latter going under the label of workflow apps.

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Mobile apps specifically designed for construction defect management, also called snagging apps, are meant to simplify surveys, inspections, reporting, communication, and more, and thus improve the handover process. Instead of filling out and updating detailed paper forms describing the nature, location, responsible person and status of each issue and taking steps to communicate this information to the right persons, snapshots are taken, the position is indicated on a floor plan, and instructions are sent directly to the responsible persons. All is handled on smartphones or tablets [7].

This represents a significant change in work procedures. As with all institutional change, it might happen that the transition is resisted [8]. This might be because the new technology is perceived not to be useful, or found to be difficult to use [9]. It is important for change to happen that the users experience relative advantage of new solutions over the familiar processes that they replace [10].

Wishing to answer the question *"Will digital quality management systems be accepted by the parties involved on construction sites?"* we conducted a case study and interviews with project managers and on-site workers on various building projects in Norway, where the RIB Capture snagging app [11] was deployed. The interview questions were guided by the Technology Acceptance Model (TAM) [9], our chosen theoretical approach. Thus, we hope to disclose any barriers to the employment of a relatively new technology that might improve the quality of buildings under construction.

This article starts with an introduction to the theoretical lens, next, the software and our research method are described. Findings are presented and analyzed according to the theoretical construct, and finally the discussion and conclusion answer the research question.

2. Theoretical Lens

Several theoretical models explaining adoption and acceptance of new technology exist (e.g. Technology Acceptance Model, Unified Theory of Acceptance and Use of Technology, Actor Network Theory, and Diffusion of Innovations) [12]. The technology acceptance model (TAM) has informed research on the user acceptance of building management systems as well as research on individual beliefs about the outcomes of BIM use [13, 14]. TAM can be viewed as an adaptation of the theory of reasoned action (TRA) to the field of information systems [15]. The model depicted in figure 1 builds on the original TAM model introduced by Davis [16] and the theoretical extensions (e.g. TAM2) suggested by Venkatesh and Davis [17]. Diverging from the original TAM and TAM2 models, the construct names 'intention to use' and 'usage behavior' have been replaced with 'behavioral intention to use' and 'actual system use' respectively. This has been done in accordance with what has been proposed by Venkatesh et al.[15]. TAM suggests that perceived usefulness and perceived ease of use will determine an individual's intention to use, and sees 'behavioral intention to use' as a mediator of actual system use. A strong emphasis is placed on the user's subjective opinion.

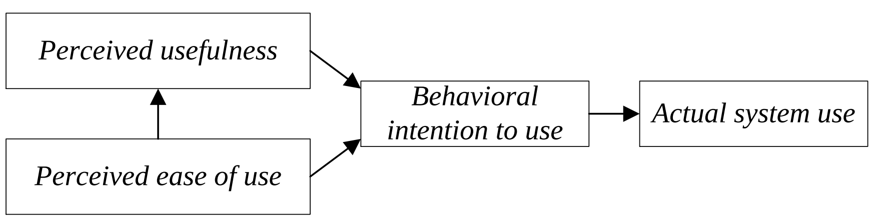

Figure 1.Technology acceptance model [9, 15, 16]

The main TAM constructs are: (1) Perceived usefulness – "the degree to which a person believes that using a particular system would enhance his or her job performance" [p.320, 18]; (2) Perceived ease of use - "the degree to which a person believes that using a particular system would be free of effort" [p.320, 18]; (3) Behavioral intention to use – users' intention of use of the system in the future [15]; (4) Actual system use – users' 'real' use of the system for performing work tasks [15]. TAM has proven its value for explaining how users come to accept and use new technology, making it a good fit for our study [19].

3. Method

A case study was considered appropriate since it allows for exploring "sticky practice based problems where the experience of the actors are important and the context of the action is critical" [p.370, 20]. We decided to conduct our main case study on an apartment building construction project in Oslo, Norway. We started by presenting the defect management application RIB Capture to the team at Contractor #1. Next, two separate inspections were carried out with RIB Capture on the case site, with a project engineer and a site manager attending. Various functions of the app were explored: registering the project, 2D drawings and involved parties, registering nonconformities, snapping photos and marking their locations in the plans, and linking each issue to the appropriate sub-contractor. We participated in the inspections to get an impression of the users' benefits from using the program and of their practical understanding of the application itself. Interviews were conducted a couple of weeks after the demonstrations, when the users, including sub-contractors, had had a chance to gain some experience with using the system. Our data was collected through semi-structured interviews, using face to face, Skype and email, with nine construction professionals working on various sites, as a way to access the interpretations of informants in the field. The interviews were conducted in October 2016, at a point in time when the design and construction had not been finalized. To supplement the research, we also interviewed professionals w three other contractors. Table 1 provides an overview of the interviews conducted. Interview guides were designed based on the Technology Acceptance Model.

Table 1. Interviews conducted.

Affiliation	Service provided	Interview technique and duration
Case project/ Contractor # 1	Project Engineer # 1	Face-to face, 45 min
Case project/ Contractor # 1	Site Manager # 1	Face-to face, 45 min
Case project/ Contractor # 1	Project Manager # 1	Email
Case project/ Contractor # 1	Carpenter # 1 and Plumber # 1	Group interview/ Face-to face 40 min
Contractor # 2	Site Manager # 2	Phone interview, 40 min
Contractor # 3	Site Manager # 3	Skype/ telephone, 40 min
Contractor # 3	Trainee # 1	Skype/ webcam, 40 min
Contractor # 4	Project Manager # 2	Email

4. Analysis

The analysis follows the structure suggested by the Technology Acceptance Model presented in chapter 2. First, the contractors` perceived usefulness of RIB Capture for carrying out their work is presented. Second, the perceived ease of use of the application in the context of on-site construction work is presented. Third, the behavioral intention to continue using RIB Capture for construction works as an indicator for actual system use in other projects is disclosed.

4.1 Perceived usefulness

Throughout the interviews, several factors were found influential for construction professionals' perceptions of usefulness. The first candidates we interviewed were site managers and a project engineer. They were convinced that a good flow of communication is important in order to keep a good flow of work. This was enabled through the application's dialogue center, as pointed out by a site manager: "*If, for example, I write that 'you need to fix a skirting board', or window moulding, then he can answer immediately and say that 'that's not my job, it's the carpenter's'. Then I can just change the contractor and send the message again'*. He added other ways in which time can be saved: '*It takes less than a minute to note a fault and take a photo and send it to the person concerned. They get it immediately*.' Furthermore, he went on to say that "*They know what they have to fix, so we can leave the flat and they can go in and do the job, so that we don't have to go through the faults",* indicating that the system enabled the subcontractor to accomplish the task without further instructions. (Site manager #2).

Another site manager further elaborated on this, explaining how productivity and effectiveness on site is increased: "*I would say that our craftspersons and subcontractors have taken a positive view because they think it's good that they can go out on the site and don't have to spend time walking back and forth to look through lots of documents and binders. It's very convenient not* *having to deal with paperwork."* Furthermore, effectivity in the office is enhanced: "*It's useful because you don't have to use documents. That's the thing. You can sort things more easily. You get the whole overview [...] You can sort things by flat, discipline etc."* (Site manager #1).

Contractor #1 had previously used a general workflow app to register nonconformities. This method in many ways resembles the traditional method of operating with paper forms and physical files. When experiencing the functionalities of RIB Capture, the project engineer interviewed at the main case study commented: "*it's easy to communicate with the different parties through the dialogue center, and take photos and have systematic documentation. It's easy compared to the traditional method."* (Project engineer #1).

We were interested in hearing how all actors perceived the new tool in terms of usefulness, including the skilled workers. After all, they are the ones doing the actual work on site. We therefore conducted a brief group interview with the carpenter foreman and plumber foreman at the main case study. They said the following: "*It's quicker, easier to keep track of things."* (Plumber foreman #1). "*In the past, we got emails with a list of faults and defects, and after we had gone through it, we went to the office to have it signed. In a way, the answer is that with RIB Capture, you don't have to make that trip to the office, and everything is in the same place."* (Carpenter foreman #1).

4.2 Perceived ease of use

After having tried the application for a few weeks on site, the users were asked how easy they perceived it to be. On site, some were skeptical at first: '*I was maybe a little skeptical of the application, but it went ok*' (Carpenter foreman #1). However, in just a short time, the users found the application easy to use and that it simplified their work. This is supported by the following quote: "*It's very easy to use. As I said to the subcontractors on the construction site: 'get to know the application, play around with it a bit.' And after a few hours they were up on it."* (Project engineer #1, Case project). '*I find it very easy to use [...] If you can use a computer, you can use this*." (Site manager #2).

In general, new digital tools require training of users. Nearly all the respondents found this easy. '*Training doesn't take long. […]. If the subcontractors ask for help, we in the construction site management help them, but there haven't been any particular difficulties'* (Trainee #1, Case project).

It was found that age can be an obstacle to using digital tools on the construction site, even though the program is not very advanced. When asked whether there were any disadvantages, one project manager who had some experience said: "*Those without sufficient smartphone competence struggle"* (Project manager #2), adding: "*And there's not much of that these days."* This was supported by another: "*RIB Capture is a modern tool in an age where mobile phones or tablets are used for most things*" (Site manager #1, Case project).

4.3 Behavioral intention to use and Actual system use.

The behavioral intention of using RIB Capture in future construction projects is evident, in spite of some initial skepticism: "*Yes, we want to use it for the next block of flats as well. We want to learn more about the software so that we can carry out a good assessment of whether we want to continue using it. […]. If it's profitable, then we'll certainly give it a go*." (Project manager #1, Case project). His colleague was even more positive: "*Word is getting around here that we are using a program that works well, so we have informed the other projects. […] I would definitely recommend RIB Capture to others. I'll be going down to a project close by shortly where we'll be doing a really big project with 440 flats, and I will definitely mention it (RIB Capture) there*" (Project engineer #1, Case project).

Contractor #3 have been using RIB Capture for several years, and never looked back. In this respect, one could say that once the decision to take the system into use has been taken, the way forward to actually use it was clear. Furthermore, they actively encourage their sub-contractors to adopt the system too. "*It was a bit challenging in the beginning to get everyone to use the system. But the more we use it, the more I think everyone will be properly informed that RIB Capture is the method used on the construction site."* (Site manager #3).

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5. Discussion

Technology Acceptance Model served well as an analytical tool for explaining user choice of technology in the context of construction projects. Table 2 shows a brief summary of the main findings. The findings indicate that RIB Capture was viewed as advantageous for various aspects of the building process.

Table 2. Summary of results (left column) in relation to TAM items [16] (right column)

Perceived usefulness	Perceived usefulness
Does the job quicker	Work more quickly
Increased productivity and efficiency	Job performance
Improves flow of communication	Increase productivity and efficiency
Makes job easier	Makes job easier
Perceived ease-of-use	Perceived ease-of-use
Easy to learn	Easy to learn, clear and understandable
Impact of experience / age difference	Easy to become skillful
Easy to use	Easy to use
Intention to use & Actual use	
Recommending for future projects	
Encouraging sub-contractors to join	

Faults and defects are a major problem in building projects; the main focus is on reducing the number of faults and defects during pre-inspections and handover. The case study and the results of the interviews presented show that using IT systems leads to great benefits and significant time savings on construction sites. The interviewees' views on using various software depend on whether the users see the potential and usefulness of digital tools. In the study, it was found that the users were willing to change their work methods, although they were skeptical at first.

In the group interview with the foremen of the carpenters and the plumbers in the case project, the interviewees explained that when they used the traditional method, they had to print out the forms for registration. Here, the way the registration was structured meant that the registrations collided between the different disciplines' activities, which made it difficult for the skilled workers to get a clear overview of their own activities. RIB Capture solved this problem, since registrations were sent directly to the appropriate recipient. When using RIB Capture to register faults and defects on the part of a subcontractor, this subcontractor will receive a simple message by email stating that a case has been opened on the enterprise. This was one of the positive aspects of the program that made the skilled workers prefer RIB Capture over the traditional method. Good collaboration between all the parties involved is a prerequisite for using the technology. This also means having a good flow of communication so that certain problems can be prevented before growing more serious.

Several players in the construction industry are loyal to traditional methods. This is often because site managers and skilled workers prefer to do the job they are used to doing, and because they have a conservative way of thinking that can cause frustration in relation to new work methods. The case project did not have this problem, since all the employees were between 30 and 50 years old and positive to the program. The program does not require high IT competence and is easy to use for everyone in the industry. The persons responsible for registering faults and defects felt this was more systematic in the program, and the access to information meant that the parties could easily learn the system. The skilled workers grew more interested in using the technology.

6. Conclusion

This paper has presented a case study of a construction project where a construction defect management app was used. By basing the study on core concepts of the Technology Acceptance Model, it became possible to answer the research question: *Will digital quality management systems be accepted by the parties involved on a construction site?* Our findings illustrate that the application was perceived as a useful tool to efficiently improve and minimize faults and defects in the completion phase of a building project. It was found that all involved parties saw the app as user-friendly, since it was easy to use and quick to master.

To gain full advantage of a digital defect management tool, it is important that everyone involved make full use of the application. In the survey, it was found that RIB Capture is likely to be adopted for use, and thereby has great potential for improving the end quality of construction projects.

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Rethinking the Complex Refurbishment Project Attributes for Building Information Modelling (BIM) Adoption

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Abstract

Uptake of Building Information Modelling (BIM) for complex refurbishment projects is foreseen as an essential resolution which will possibly increase the BIM adoption rate and eventually play a major role in transforming the construction industry. This anticipation is primarily based on the success of BIM with regards to complex construction operations, management, performance and productivity improvement. Various architecture, engineering and construction (AEC) key players have promoted the adoption of BIM and highlighted its significance in enhancing project delivery. Despite the envisaged benefits and feasibility of BIM adoption for complex refurbishment projects, many small and medium enterprises (SME) are still reluctant towards BIM. Though the incorporation of BIM in the New Zealand context is also similarly expected to move the construction industry forward, little has been reported in the literature to address the impact of refurbishment project attributes towards BIM adoption. A case study of tertiary education multipurpose facility project is adopted. Semi-structured interviews were conducted with informed project stakeholders and BIM experts outside the project based in New Zealand with the aim to identify refurbishment projects attribute and how it contributes to BIM adoption barriers for refurbishment project stakeholders in the construction industry in New Zealand. The benefit of this study is that it leverages the traditional refurbishment practice towards being BIM capable, and thus enable BIM uptake for refurbishment project stakeholders at the pre-maturity stage in New Zealand tertiary institutions.

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Keywords: Building Information Modelling (BIM); Refurbishment project attribute; Project stakeholders; BIM adoption barriers;

1. Introduction

Building Information Modelling (BIM) is an emerging technology and its implementation is expected to lead to improved performance in construction processes throughout the life cycle of an existing building facility. Despite BIM benefits to construction projects [1], its delivery and uptake has been reported to be slow for existing building projects [2]. Anecdotal evidence reveal that the decline in uptake is due to project fragmentation [3], isolation, lack of collaboration and information sharing within the construction firms [4, 5]. Besides, the refurbishment projects are of risky essence [6], and very complex in nature [2, 4]. In addition, the U.K government, as part of enhancing adoption of BIM in the public sector earlier in 2016, targeted minimizing life cycle cost by 20% and 80% reduction in carbon by 2050 [7]. Similarly in Netherlands, BIM is now a mandatory requirement for governmental projects towards energy refurbishment, while in Denmark, the government requirement for BIM implementation since 2007 has influenced its use for energy efficiency target [8]. Considering New Zealand construction environment, a previous survey regarding BIM adoption affirmed that within construction organizations, 38 % used BIM for most projects, 20 % used BIM for

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few projects, while 42 % of organizations did not respond indicating low level of engagement in projects models among project stakeholders [9]. Although the need to investigate BIM relationships with attributes of projects to enhance BIM adoption potentials has been highlighted by [10-14], significantly, the project attributes can have different potentials to different organizations, projects or individuals [15]. In addition, the project attributes can give different results in different construction environment[16]. Hence, as BIM tool is generic [14, 16, 17], this means that these project attributes can be influenced by culture and collaborative environment for effective BIM adoption [14]. Therefore, the current authors believe that identifying the refurbishment project attributes in a given environment can be useful to understanding how to motivate adoption of BIM. Hence, this portrays the need to investigate refurbishment projects attributes to maximise BIM adoption [18]. Hence, the study aims at identifying the refurbishment project attributes for client-organisations such as tertiary institutions to address the potentials of BIM adoption for the multipurpose existing buildings in New Zealand. To achieve these objectives, this study starts with literature review of existing studies on BIM adoption for refurbishment projects and the discussion about project attributes and perceptions of refurbishment stakeholders in the New Zealand construction environment. Therefore, a descriptive interpretative research was conducted by using semi-structured interviews. This approach is suitable to allow the investigator to disallow presuppositions regarding the phenomenon in search of the true meanings and to have deeper understanding of the phenomenon as experienced by the experts.

2. Research Background

The potentials of BIM adoption is to improve the refurbishment work flows so as to mitigate cost overrun, critical decision and save time by project stakeholders [2]. There are authors that have contributed to BIM adoption study for refurbishment project. Volk, Stengel [19] focused on the technical problems related to BIM implementation. This includes updating and handling of uncertainty of data information of BIM in existing buildings. Also, a study proposed a framework to understand tools and drivers that motivate BIM adoption for refurbishment projects [20, 21]. In addition, another study also focused on the clients as homeowners preferences and how it influences BIM adoption for refurbishment projects [5]. Essentially, homeowners' choice is mainly "cost" against the method of refurbishment as "thermal performance" preferred by contractors. Furthermore, there is an investigation for the essential barriers to hinder BIM adoption for housing refurbishment [22]. The barriers are twofold; the first is from the clients indicating lack of knowledge about refurbishment technologies, while the second is the construction professionals indicating lack of skills, and fragmented practices. Therefore, these construction professionals may underestimate the real BIM benefit for refurbishment projects. Although one benefit of BIM for refurbishment project is that it enables life cycle data management which facility managers (FM) can use to maintain an existing facility [3], [19] suggested that there are hindrances to adoption of BIM for existing buildings considering the lack of research to investigate the bottleneck barriers for refurbishment stakeholders and facility managers (FM) in adopting BIM for existing building facilities. While a previous study is of the view that the bottleneck barriers is due to low participations of FM and refurbishment stakeholders towards the development of strategies to adopt BIM for refurbishment projects [23], other authors believe that the main barriers relies on the type of attributes identified on different construction and refurbishment projects [10-14].

3. Methods

This study adopted a semi-structured interview by allowing the respondent to actively engage them to sharing their views using their own terms [24]. The respondents are the experts in construction industries in New Zealand. Considering the limited nature of expert in refurbishment project execution and with BIM experience, a case study refurbishment project and snowball approach was adapted. The first approach was to identify a refurbishment project case study whereby its previous operation contains a number of stakeholders that were involved in its execution. The second approach was to identify the potential stakeholders with deeper knowledge in refurbishment project execution in tertiary institutions in New Zealand. The refurbishment project case study is a multi-purpose building facility in a tertiary institution in Auckland. This project was selected based on the difficulties and challenges during its execution. Although, the project was fast tracked, there were many loses and uncertainties during the project execution. Request for interview participations was sent out, the initial interviewers suggested potential participants. In total, 14 people were interviewed that accepted our interview request. This sample size is considered appropriate for the sample size as [25] affirmed that 12 interviews are sufficed to achieve saturation. Therefore, this study employs a descriptive interpretative research to understand the project attributes of refurbishment project and to formulate mitigation plan to enhance BIM adoption. According to [26], a descriptive interpretative methodology seeks to extract meaning from the experiences of several refurbishment professionals. This process allows a deeper understanding of individuals experience about refurbishment barriers and setbacks to BIM adoption. This is because poorly conceptions can be prevented when the researcher is in active inquiry with the participants [27]. The research participants were interviewed according to their individual preferences for example is by the use of face-to-face interview, and online communication tool platform through Skype. The interviews were held in Auckland, New Zealand. Before conducting the qualitative interview, approval was sought from the [28]. This was to protect the safety, privacy, health, welfare and social sensitivities of the various participants involved in the provision of research data. Table 1 details the demographic representation of the research participants

The interviews have been recorded with recording device both for face-to-face interview and the skype interviews. The transcription of the audio interview into text write up was done manually by the researcher. The interview transcripts were categorized based on the simple themes and analyzed using a pattern coding technique.

Table 1: over view of the participant demographic information

CODE	Categories of participants	No of experts	Years of experience
PM1, PM2	Project Managers	2	5 – 12
MC	Main Contractor	2	8 – 15
SB1, SB2	Sub-contractors	2	10 – 16
M1, M2, M2	BIM Managers	4	4 – 8
C1, C2	Consultants	2	10 – 22
AR1, AR2	Architects	2	8 – 15
CR	Client representative	1	8 – 12
SU	Space Users	3	6 – 10
Total		18	

The demographics of the participants reveal different levels of experience, and the categories of participants majorly from client organisation (tertiary institution). This could enhance the transferability of the results to readers for their applications, and this can promote the validity and reliability of findings [29]. Adequate care was put in place in order to avoid mistakes during the transcript transcribing stage [30].

4. Results and Discussion

For a descriptive interpretative research, the analyses are semi-structured, and therefore the qualitative interview starts with open questions that allow the opportunity for the interviewer to explore themes or responses further [31]. However, thematic analysis was carried out with suitable coding scheme to identify units of meaning from the main statements and are classified into recurring themes. In this section, three reoccurring themes were analysed: The nature of refurbishment projects in tertiary institution in New Zealand; The challenges of refurbishment project to motivate BIM adoption; the solution to adopt BIM to solve refurbishment project problems.

4.1. The characteristics of refurbishment projects?

All the interviewees were asked to briefly describe the nature of refurbishment projects they have participated for organisations such as in tertiary institution.

4.1.1 There is a periodic refurbishment for most of the existing buildings.

All the respondents stated that most of the existing buildings are multipurpose building and can be refurbished annually due to several demands by clients or organisation and government. Such demands as highlighted by the participants includes; “Many tertiary institutions would want to meet up with the international learning standards. So, there is the tendency that such organisations will embrace modern methods changes and teaching methods, and as well, try to embrace a collaborative modern and open learning method between different groups and learners […]

A similar number of participants noted that during there are other attributes persistent in the management of refurbishment projects. For example, half of the participants indicated that "there are lot of stakeholders and user involvement to determine a particular layout […] In addition, all the participants also highlighted that "There is lack of ability to communicate new layout to who will be occupying these spaces […]

4.1.2 There is always lack of building information.

All the participant indicated that "There are lots of refurbishment project which are starting with poor building information […] one of the participants also stated that "as a consultant, there are lots of uncertainties to encounter which affects some stakeholders like the contractors who mainly bears the risks during the construction stage […] while another participant explained that "as a sub-contractor, I think that refurbishment projects has thoroughly unknown factors […]

4.1.3 There is fear on the cost of BIM.

Majority of the participants highlighted that most stakeholders tends to avoid BIM adoption due to fear of the cost for BIM. For example, "A lot of things come back to old buildings. Existing buildings in the past 15 years are not done with BIM. There may be design document that are not suitable for design activities for refurbishment project. Old tradition is not very efficient especially when it involves manual measures, and these tend to be expensive to upgrade with BIM. These days, traditional method is prone to error. Added that most refurbishment project starts with poor project information […]

Hence, the research participants concluded that with the typical nature of these refurbishment project, there is always poor assumptions and the most significant in New Zealand is that of typical project duration when doing a refurbishment of existing building.

4.2. The challenges of refurbishment project that motivates BIM adoption?

To gain deeper understanding on the nature of the refurbishment projects as found in tertiary institutions in New Zealand, interviewees were asked how the nature of complex refurbishment projects influence BIM adoption for existing buildings.

4.2.1 Poor project collaboration

The participants believe that to improve collaboration is very significant in this venture. According to a participant: "It is about working with good team. When all get on to a common goal, it is easier to manage these unknowns [...] Hence, as long as you have positive approach and people you work with have the same positive attitude in a rewarding environment is what matters. If not, the unknowns will create huge problems for the stakeholders. While another participant: indicated that "I do think that the personality and experience of the people involved brings out a greater outcome […] The interviewees opinions are in line with previous authors that effective collaboration is an essential tool for improved project performance and supports the view of [32] for improved collaboration for project stakeholders. Also, according to [33], team communication and collaboration is critical to the success of building construction. Considering previous knowledge on BIM adoption for refurbishment project [5, 34, 35],

4.2.2 Peoples attitude

The attitude to technology adoption is still a challenge. Many of the participant highlighted that: "if you bring a really rigid attitude to technology, and you are a perfectionist, you are going to be really upset about that, but if you are flexible, adaptable and you understand, and you think quickly and carefully what alternatives are, you definitely get a good outcome […] Half of the participant observed that: Most contractors may not be honest to the cost of the project and therefore they tend to cut down the cost of the project to ensure that the project is awarded to them […] Another participants supported by saying that:
"The cut down cost impact on the finishing trades and interior trades, so they try to recover some of their lost time and the programmes are quite regularly cut […]

4.2.3 Lack of skills

Many of the participants emphasized there are still skill shortages to manage refurbishment projects and these impacts on accepting new technology for maximum project performance: “Restructuring older houses with older technique to a new technique can be very challenging […] Hence, most of the document produced in a traditional method lacks complete as-built documentation. Another interviewee who supported in view stated that: “Most old buildings have not been done with BIM especially in the past 15 years. Starting with documentation, most of these documentations are not suitable for refurbishment project execution […]

4.2.4 Poor project documentation

All the participant highlighted that: “there are lot of refurbishment project which are starting with poor building information. Which means BIM is a significant requirement for upfront investment in acquisition of building information. For example “One thing we care for is having a complete information for all the stakeholders but when the information is unavailable, there will be delay in execution of projects […] Consequently, the participants believed that when this information is not properly managed, it results to project difficulties. Two other participants supported: “There are a lot of assumptions, or incomplete records of buildings. There is incomplete information most times, and it takes time to obtain this information […] Hence, the lack of information and management may have effect on the integrity of project outcome from the view of few participants: “When a program is drawn, and there is lack of information, this will cause delays […] “Based on the provided traditional building information, the contractor makes assumption based on the uncertainties and when these does not go as expected, the contractor will start to lose money […]

4.2.5 Nature and scope of the refurbishment project.

About one-third of the participant believed that adoption of BIM for refurbishment project should be relied on the building type. For instance: “It depends on the type of building to be refurbished and also by case by case and quality of building […] “It all depend on the nature of scope of the refurbishment project entails […] “It depends on the nature of the building that is being refurbished, I think some are risky than others, and older building might have hidden secrets and problems within them and with poor infrastructure, like rewiring that you submit for needs doing or foundation extra works, compared to a new building where it might be what one could call a “lacking of promise of paid jobs and a better of do-ups […]

4.3. The solutions towards adoption of BIM for refurbishment projects

As highlighted by the participant, there are several ways to increase BIM adoption. These has been discussed under the following paragraph;

There is a need to develop program and assessment criteria to check each stage. For instance: “At the start of every project, there should be something called the BIM execution plan. Where this is not set up at the early stage can be a huge risk *“Establish a program, list a set of mile stone to adopt BIM for the project and set up an assessment to check each stage”* These was in line with a previous author regarding using a development assessment criteria to improve the issues of cloud in BIM Alreshidi, Mourshed [32].

The laser scanner can be used to pick points. This would be more efficient according to the participants when the whole ceiling is turned apart for manual measuring for example. While few of participants argue that the main thing is uncovering the unexpected, majority of participant believed that physically, they can try to mitigate that by ensuring that the point cloud is done. In this way, the main users can trash so much about those issues about coordination and ensuring that the proposed signs does align with the physical building that exist on the site and the way to mitigate that is modelling the existing building and the point cloud carries the information about the existing building.

Develop a positive culture. Majority of the participants has concern about positive culture in our industries towards innovation such as BIM: *“I think, you need good team people, a positive culture. You also need to have good document to reduce the risks”* The first thing is about the leadership of the project. So, the key players need to have good communication. Creating a good culture of communication and perhaps addressing these things at the beginning of the project that these are the way we work, meeting times etc.

Focus on the building section that require refurbishment other than the whole entire building complex: “In the past, as highlighted by a participant, the whole building model is done for a whole existing building, these are not necessary, it increases the cost of BIM, and makes the model to lack focus at that moment. *“BIM should be implemented for that particular level of the building, where the refurbishment is to be taken place”*. This would help the stakeholders to produce a better-quality model, and with less cost. The laser scanner can merge these parts refurbishments point clouds capture to become one full building model. This contrasts [34] BIM adoption framework, who suggested whole building modelling which can make the BIM implementation very expensive.

The time frame should be made more accommodating to work out a program for the refurbishment project BIM adoption effectiveness. Hence, instead of minor capital work done yearly, it can be run on two-yearly bases. So, when the contractors are pricing the project, they do that for two years’ time bases, hence, they can give room for a lot of BIM consideration. This will help to get the outcome before the project starts. The short time frame also plays a part to neglect BIM adoption decision.

Make BIM an obligation to enhance adoption of BIM for refurbishment projects. For the educational institution facilities, it is important to use this as a new technology, as a kind of obligation for the students. Moreover, city council in New Zealand can also incorporate BIM as a regulatory factor during the consent. Hence, to improve the level of adoption for BIM, there should be a legislature to mandate BIM into law.

Finally, by considering these processes remains a better avenue to motivate adoption of BIM for refurbishment projects in New Zealand. Starting from the complex buildings in tertiary institutions as found in New Zealand, these existing buildings are refurbished periodically to suit a particular purpose and demands a high-performance standard. Majority of these houses are traditionally managed. The client organisations who manage these buildings should make effort to consider engaging with their refurbishment stakeholders to consider adoption of BIM for the management of their existing buildings in tertiary institutions. Furthermore, New Zealand government should also consider making a stronger awareness on the existing buildings in tertiary institutions through authorising BIM for every existing building in New Zealand tertiary institutions.

5. Conclusion

This paper examined the characteristics of refurbishment projects and how its attributes contributes to BIM adoption barriers. The results show that despite most of the complex buildings in tertiary institutions are refurbished annually with traditional methods, there are still many challenges faced by her project stakeholders in managing these existing projects. BIM adoption can leverage the potential to improve the performance of these projects. However, the study pointed out several stakeholders’ traits which impacts on BIM adoption including, people’s attitude, lack of skills and expertise, lack of information management, lack of openness, and nature and scope of refurbishment projects. The study also offered solutions to BIM adoption such as (1) Develop a programme and assessment criteria, (2) Adopt tools for information sharing/collaboration, (3) Develop a positive culture, (4) Re-address project timeframe, (5) Focus the laser scanner survey on the required space for refurbishment, and (6) Make new policies for BIM adoption motivation. This research contributes to the current knowledge on BIM adoption for refurbishment projects by providing solutions to client organisations, and FM in tertiary institutions in New Zealand and other stakeholders that refurbishes multipurpose buildings for the formulation of effective strategies to adopt BIM. Further studies will investigate the real benefits of BIM for refurbishment project stakeholders.

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Simulating interaction dynamics of refurbishment project stakeholders through agent-based modeling towards enhancing BIM adoption effectiveness

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Abstract

Building Information Modelling (BIM) is an IT enabled technology that supports information sharing, access, update of data and use, and allows storage of information and management. While the technology itself is not new, similar approaches have been in use for the construction of new builds, but the refurbishment domain is yet to catch up with the ability to exploit BIM benefits. The study offers an avenue to investigate the effectiveness of adopting BIM for complex refurbishment projects through a simulation of the interaction of refurbishment project stakeholders network using agent-based modelling performed through a parameterized Bayesian network. Previous investigations show that stakeholders hold the common ground to make effective decision towards adoption of BIM for complex refurbishment project. The aim of this paper is to present the results of current simulations made using Hepar II network on the interaction of project stakeholders for refurbishment project case study of a tertiary institution in New Zealand. In addition, the paper investigates whether there are benefits towards adoption of BIM considering the influences of the modification of the threshold error parameter on the final factor observation states.

Peer-review under responsibility of the scientific committee of the Creative Construction Conference 2019.

Keywords: Building Information Modelling (BIM); Refurbishment project stakeholders; Interaction Networks; agent-based simulation

1. Introduction

BIM is a construction management tool for managing engineering problems that involves design, energy efficiency analysis, maintenance, documentation, and delivery for all different phases of project life cycle [1]. A strategic approach to BIM adoption requires the incorporation of people, process, and technologies on timely bases, it also leads to capacity buildings and good managerial improvements [2]. Recently, BIM has captured the attention of the construction sector due to its widely recognized benefits for building projects [3, 4], yet the use of BIM for refurbishment projects is just emerging [5]. Based on the existing literatures, while [6] advocates that to maximise BIM adoption for complex refurbishment projects, there is a need to examine whether there is real BIM benefits through a healthy interaction of refurbishment project stakeholders, following that the stakeholders are the actors who influence the operation of various economic actors in various ways [7]. Although, social interaction fosters the emergence groups with a common interest of different stakeholders to a shared solution. Hence, the decision to

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innovation becomes a bidirectional communication process which requires specific programs and skills and at the same time coordinate many players, variables, problem solving and conflicting interests. Therefore, the use of decision support systems such as Bayesian models based on quantitative methods can investigate healthy interactions in projects [8] in other to identify BIM effectiveness. Therefore, the main objective of this study is to compare traditional refurbishment project network and BIM prototype network by simulation of uncertainties (error conflict) through the network of project stakeholders. In other to achieve the objective, this study is structured into three parts. The first part is the literature review which discusses about stakeholders and the use of agent-based modelling, the second part discusses about the methodology while the third part presents the result and the analysis, then followed by the conclusion.

2. Literature review

The aim of literature review is to introduce the importance of stakeholders and as well as the agent-based modelling in construction projects. These factors have been used in this study to investigate the effectiveness of BIM for refurbishment project based on project network interactions.

2.1. Stakeholder theory and engagement

The concept of "stakeholder" has been said to be derived from Economy, indicating that the power of organisations depends on the relationship of its stakeholders [9]. [10] has documented a chronology of the concept of stakeholders and their key constructs in theory and their identification in construction projects. The refurbishment stakeholders are those actors that have an interest in a particular refurbishment project [11]. Accordingly, one characteristic of the AEC industry is the unconventional nature of networks of stakeholder interaction which constitute building and construction projects [12]. This has contributed to the challenges within projects including knowledge transfer in organisations and the diffusion of innovation propensity [13]. Since the complexities in refurbishment project requires specific tools, an investigation of project interaction by comparing traditional method vs BIM method would help to identify the knowledge of information exchange among different and encompassing stakeholders involved in refurbishment project BIM adoption decision. Therefore, the current study investigates within stakeholders interaction because through this means, a real-world problem will be solved [14].

2.2. Agent-based model of stakeholders' interaction

Agent based modelling (ABM) is a computer simulation for analysing complex interaction between multiple agents. In other worlds, the simulation is carried out on "the observed world called actors (agents) with certain behaviour which is dependent on the state of the environment" Each of the agents can act locally in response to a stimuli when they communicate with other agents [15]. ABM dynamics models have been widely used to investigate social interaction in stakeholder networks and these would be typically reproduced at the participatory decision-making processes in construction projects [16]. For example, the social network analysis has been used to simulate interaction of project stakeholders [17], but lacks the capacity to determine the level of performance of networks between traditional projects and BIM projects, and to identify which network favours identification of project uncertainties. To correct the deficiency in social network analysis (SNA), there are other set up such as "Virus in a network" using Netlogo software [18]. This method of simulation has benefits but also limited to assessing the general capacity of the network but cannot determine the individual stakeholders' contribution or sensitivity within the project network. Therefore, the current study covers this gap by adopting Bayesian network using Hepar II model to simulate the refurbishment project network for investigation of real-time benefits between the two project networks.

3. Methods

An agent-based Bayesian network has been built to model and simulate the interaction of project stakeholders for a recent completed refurbishment project is presented. The project stakeholders are represented by the nodes of a network linked to each other based on their social interaction. A questionnaire designed to obtain the interaction network is administered on the project stakeholders who participated on a recent refurbishment project in a tertiary institution in Auckland. Owing to the shortage and lack of interest of refurbishment stakeholders on BIM interest, a snowball technique was used to identify and nominate the participants who were involved in the project to enable modelling of the interaction network to locate the potential interviewees. Before conducting the quantitative interview, approval was sought from the [19]. This was to protect the safety, privacy, health, welfare and social sensitivities of the various participants involved in the provision of research data. Table 1 details the demographic representation of the research participants

Table 1: over view of the participant demographic information

CODE	Categories of participants	No of experts	Years of experience
PM1, PM2	Project Managers	2	5 – 12
MC	Main Contractor	2	8 – 15
SB1, SB2	Sub-contractors	2	10 – 16
M1, M2, M2	BIM Managers	4	4 – 8
C1, C2	Consultants	2	10 – 22
AR1, AR2	Architects	2	8 – 15
CR	Client representative	1	8 – 12
SU	Space Users	3	6 – 10
Total		18	

The demographics of the participants reveal different levels of experience, and the categories of participants majorly from client organisation (tertiary institution). This could enhance the transferability of the results to readers for their applications, and this can promote the validity and reliability of findings [20].

The nature of the interview was a collaboration questionnaire designed to extract the intensity of interaction among the project stakeholders. For example, the project stakeholders can be asked to list the number of stakeholders they interacted during the project and how often they interacted. The rate of interaction can be measured with “frequent” “less frequent” and “none”

4. Results and Discussion

We adapted Hepar II network using Bayesian network model. The Bayesian network models are acyclic directed graphs modelling probabilistic dependencies and independencies among variables. In this study, the dependencies and independencies occur between nodes or also called the project stakeholders. The graphical part of Bayesian network shows the structure of interaction among the project stakeholders and this are quantified by conditional probability distributions [21]. In order to adapt Hepar II network, we considered the effects of the level of complexities of the networks but less consideration to the level of initial error break-out. The disorders are considered as the error introduced into the network and are allowed to simulate through the network as “designed error” The time to identify the error, error percentage, recovery chance is measured by each node in the network. The nodes are set as observers with a defined probability of occurrence of 0.3 %, 0.3 % and 0.4 % respectively. Table 2 shows the parameters for the Bayesian network model.

Table 2: the parametric used by GeNIe

Parameter	**Definition**	**Applied values**
Target node	Number of individuals generating design error	Percentage of individuals
Observation node	Frequency of design error checks to identify errors	Number of weeks
Time	Time to identify error	Final percentage
Error percent	The quantity of error perceived by each node	Number of percentage increase
Recovery chance	Probability of an individual not continue to do error	Number of percentage decrease

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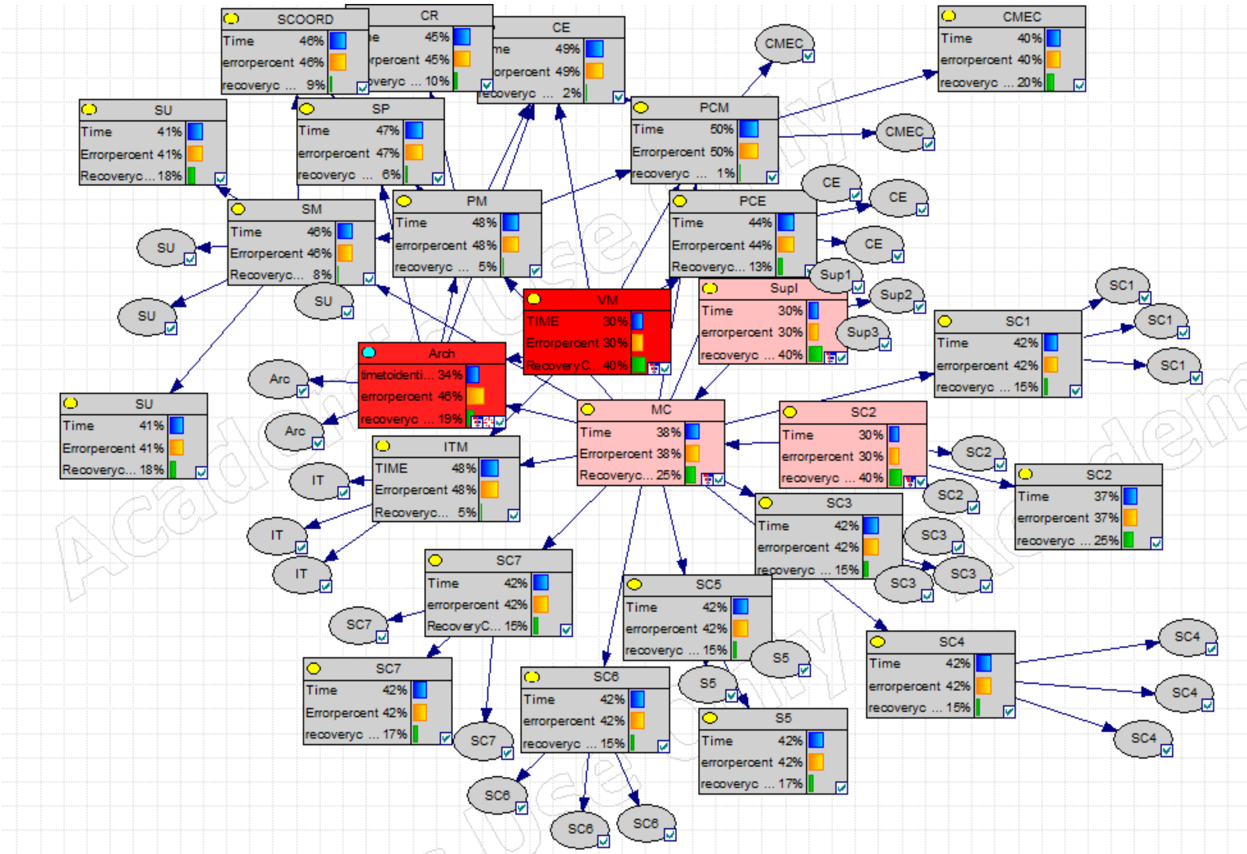

Figure 1: The traditional project network A

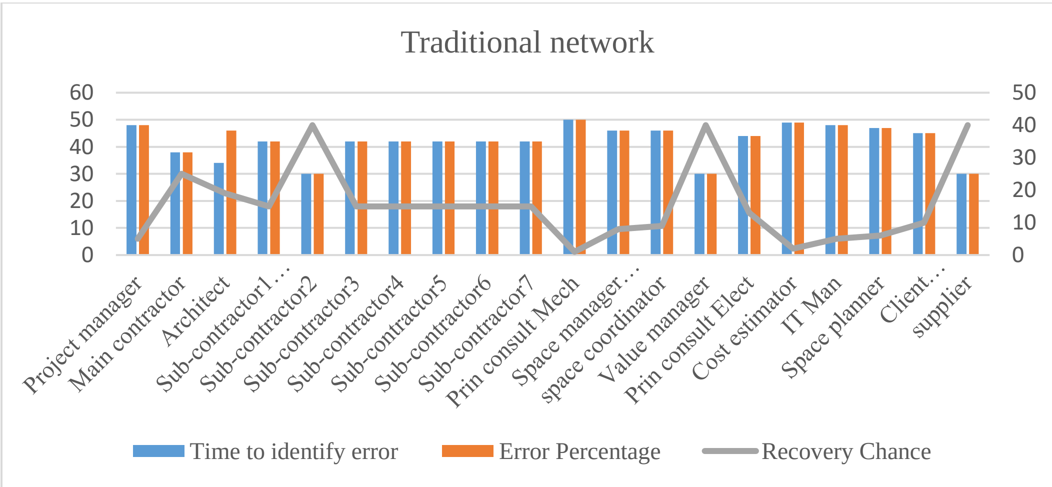

Figure 2: Simulation result for the main traditional network

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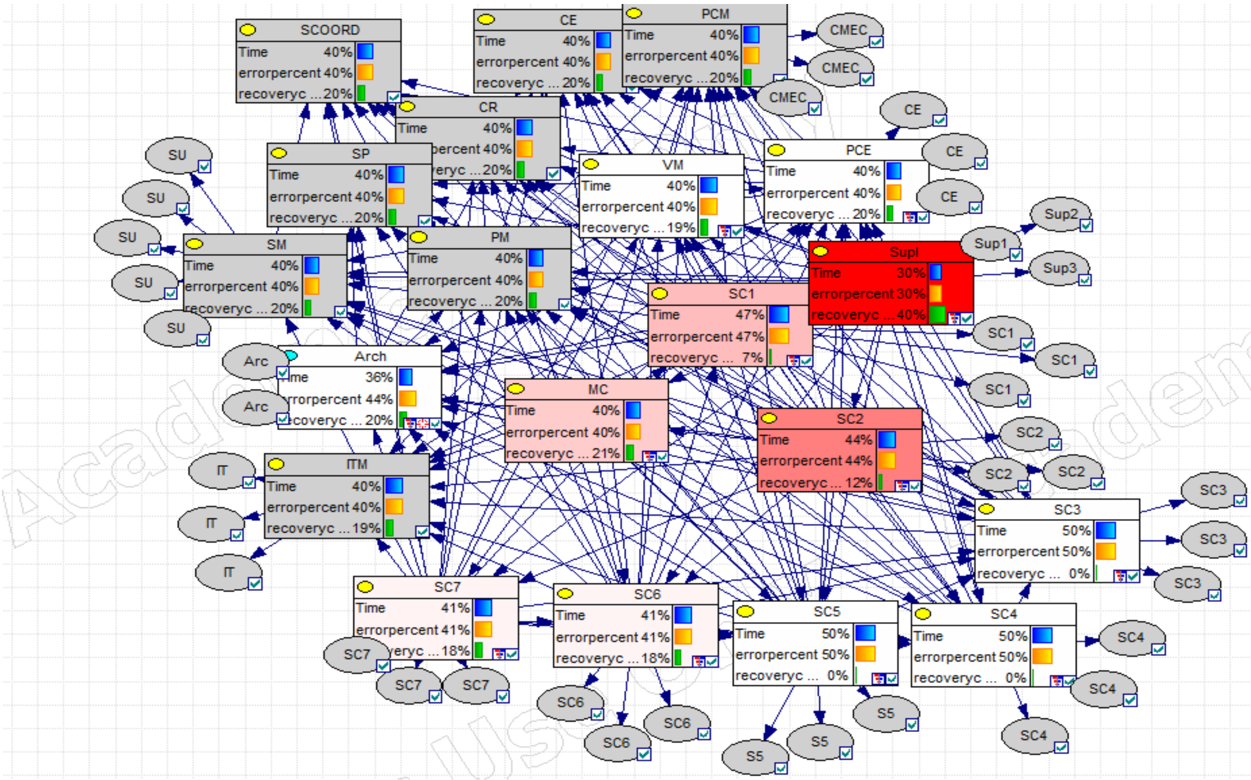

Figure 3: The virtual BIM project network

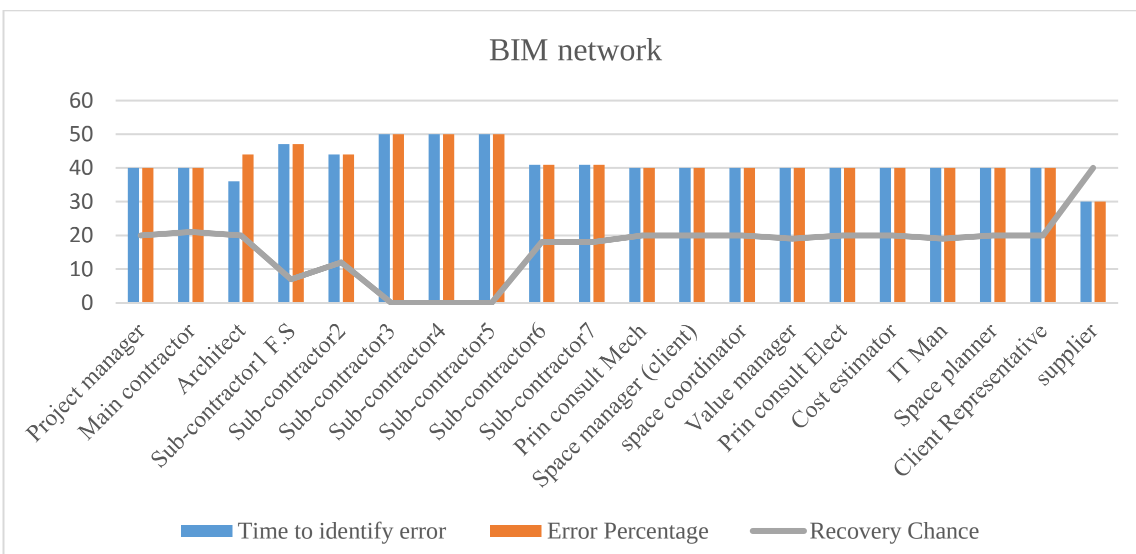

Figure 4: simulation result for error propagation on BIM network

5. Conclusion

This paper examined the relationship between the traditional refurbishment project network and a BIM prototype network in the same environment using Bayesian network model to investigate if BIM would be effective and beneficial for stakeholders who refurbish existing buildings in a tertiary institution setting. The result indicate that the

Bayesian network was very effective in identifying the impact of the different stakeholders in the project network. The error introduced at the architect domain has different impacts on the two project networks. Although the two networks show the same pattern of error propagation, there are differences based on the impact of errors on the project stakeholders. The agent-based model indicates in each network (Figures 1&3) the project stakeholders who are likely to be highly influenced by the introduction of error by different their colours on the nodes. The red coloured box/es indicates that the stakeholders are negatively impacted while the white colouration shows positive impact. This is also evident based on the simulation result of the error propagation observation of each node as shown in Figures 2&4). The plots represent the overall diffusion of errors, recovery time, and the percentage of error perceived.

In summary, the result shows that it takes more time for traditional project network to recover from uncertainties such as design error compare to BIM network. It also indicates that stakeholders in a BIM network almost identify errors and recovers at the same momentum compared to the traditional network. The main architect who makes the error recovers instantly at the BIM network compare to the traditional network. This is because of the improved linkages (or edges) offered by the BIM network creating a stronger social network with increased collaboration between the project team members. Overall, the simulation result is a justification for BIM adoption for refurbishment projects regardless of the size of the project. Future work might examine the identification of real benefits of BIM on the refurbishment project using sensitivity analysis. Another option might be a desktop audit, which might be suitable to validate the different networks as shown in the study.

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USING AUGMENTED REALITY FOR MASONRY AND CONCRETE EMBED COORDINATION

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Abstract

Missing or misaligned embeds, sleeves and penetrations for concrete and masonry construction have historically caused disruptions and errors in commercial construction resulting in delays, rework and cost overruns. In order to locate embeds, sleeves and penetrations through the traditional process requires a special set of coordination drawings to be produced called "lift drawings." The "lift drawings" are essentially elevation views of critical wall and foundations elements which show the exact location and alignment for the embeds or penetrations. Producing these "lift drawings" is a time consuming and tedious process that is typically undertaken by the construction management professionals in order to assure that these elements are located properly within the building.

In the age of BIM this process of producing "lift drawings" for embeds, sleeves and penetrations should be coordinated and streamlined using BIM and augmented reality to reduce the work effort and provide greater efficiencies. This paper seeks to discover ways in which BIM combined with augmented reality and traditional surveying hardware can improve the process of embed, sleeve and penetration coordination.

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Keywords: Augmented Reality, BIM, Coordination, Surveying

1. Introduction

Concrete or masonry embedments ("embeds") are used extensively in commercial construction, embeds serve as connection points between dissimilar materials. Oftentimes you see steel embeds used in concrete and masonry construction to allow the connection and attachment of structural steel members to a previously installed concrete or masonry structure. A traditional problem with embeds is that oftentimes they bridge a gap between two separate subcontractor's scope of work, and if they are excluded or omitted those two separate scopes cannot be efficiently integrated together. Since embeds serve as the necessary link between the two separate scopes of work (e.g. concrete and structural steel) that dependence often times leads to a points of contention and lengthy disputes. Contractors have long recognized that embeds can lead to conflict resulting in costly and time consuming rework, and therefore have used a number of different strategies to defuse the problem. Despite best efforts the problem of embed coordination still exists in the construction industry.

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In the case of concrete construction if embeds are omitted or misplaced it will lead to costly rework because as the saying goes the “die has been cast.” Post-setting concrete embeds after the concrete has been placed and cured is extremely disruptive to the construction process. In masonry construction some embeds need to be placed as the walls are laid and others are placed after the wall is constructed, in either case if the embeds are omitted or misplaced the rework involved is both costly and time consuming similar to concrete construction. The figures below illustrate some typical examples of embeds used in both concrete and masonry construction respectively.

Figure 1. Embeds in concrete and masonry construction.

Traditionally embeds are located using “lift drawings” which are essentially drawings produced in the elevation or plan perspective which show the embed location in an x-y plane. These drawings are typically produced by a member of the construction team who is tasked with coordinating the embed placement and inclusion. The embed locations are dimensioned in both the x and y plane on these two dimensional drawings. The process of producing these drawings and accurately placing the embeds is both time consuming and labour intensive.

Recently, representatives from our School met with members of our industry advisory council and they reiterated the need for a novel solution to this systemic problem. Our industry advisory council (IAC) is made up of construction industry leaders in the South-eastern portion of the United States, and part of their service to our school includes them bringing us current and relevant problems within the industry to use as research topics.

The representative from the industry advisory council who brought us this problem suggested we explore how Building Information Modelling (BIM) might provide some solutions. BIM is increasingly integrating traditional processes with more data-rich information that is streamlining the overall construction processes [1], therefore considering how BIM could be applied within a novel solution to this problem would be prudent. We took that recommendation one step further and wanted to explore not only how BIM might be used to resolve the problem but further how augmented reality combined with BIM could present a novel solution.

As opposed to virtual reality, augmented reality overlays the virtual world with the real world [2]. To do this augmented reality has to anchor a hologram to the real world environment via a series of sensors and devices through a process known as registration [3]. One of the most common augmented reality devices used in the market today is the Hololens made by Microsoft. The Hololens was selected as the augmented reality device for this study because we discovered that many industry partners in the school’s IAC were using the same device in professional practice. Furthermore, in an industry-wide survey conducted by JB Knowledge in 2017 which included over 2,500 survey respondents, they reported that one of the most disruptive technologies that were “driving innovation” (p. 64) in the construction industry was augmented reality [4]. A fact that is repeated in their follow-up reports in 2018 and 2019 [5] [6].

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Lastly, previous research has illustrated a favourable outcome in productivity and quality when augmented reality solutions were applied [8]. Therefore, it is imperative that solutions to the construction industry's anaemic productivity [7] be met with innovation and a platform that encourages the use of augmented reality.

2. Methodology

The goal of this research was to develop an experiment which would give us some early indications on whether augmented reality would be an effective piece of technology to utilize in resolving the problem of embed coordination. As stated above often times in construction embeds are omitted and misplaced leading to costly rework. The basic concept behind the experiment is that we would simulate embed verification on a construction site and utilize our construction management students as our test population to determine whether or not augmented reality allows for more efficient and accurate embed verification than traditional 2D "lift drawings."

For the experiment we decided to utilize and unfinished space within our department's building which has exposed masonry walls. The space itself was modelled using Revit and further to assure that the model was as close as possible to the actual construction a laser scan was used to match existing conditions. After the space was modelled we randomly placed steel embeds (Steel Plates, Angle Iron) within the model representative of what might be encountered on an actual construction site. See figure 2 below for an images of the model and the placement of the embeds.

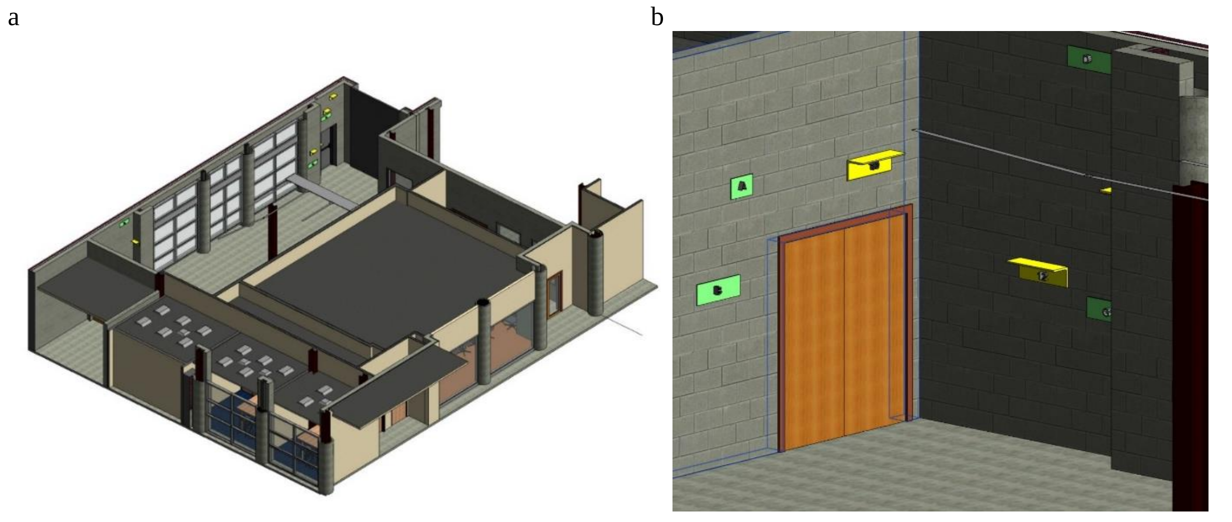

Fig. 2. (a) model of entire space (b) close-up of steel embeds

We exported this model to our augmented reality device (Hololens) using a relatively new app called "Hololive." This app allowed for direct export to the AR device from either Autodesk Revit or Navisworks. Also from this same model we produced 2D "lift drawings" as seen in the figure 3 below.

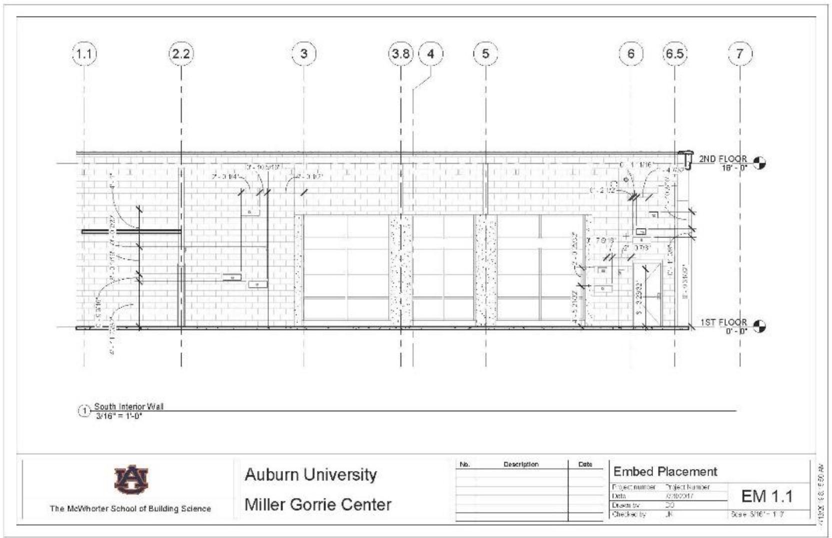

Fig.3. Example of 2D lift drawings

After the model was created templates were made of the steel embeds to hang on the wall. We mocked up the embeds with templates made of poster board. These templates were then precisely located with a Robotic Total Station. It was important to us to place the templates in their accurate positions so that we could investigate how drift and alignment issues might impact our ability to utilize the augmented reality device. See figures 4 & 5 below for pictures which show the layout of the templates and their placement within our experiment space.

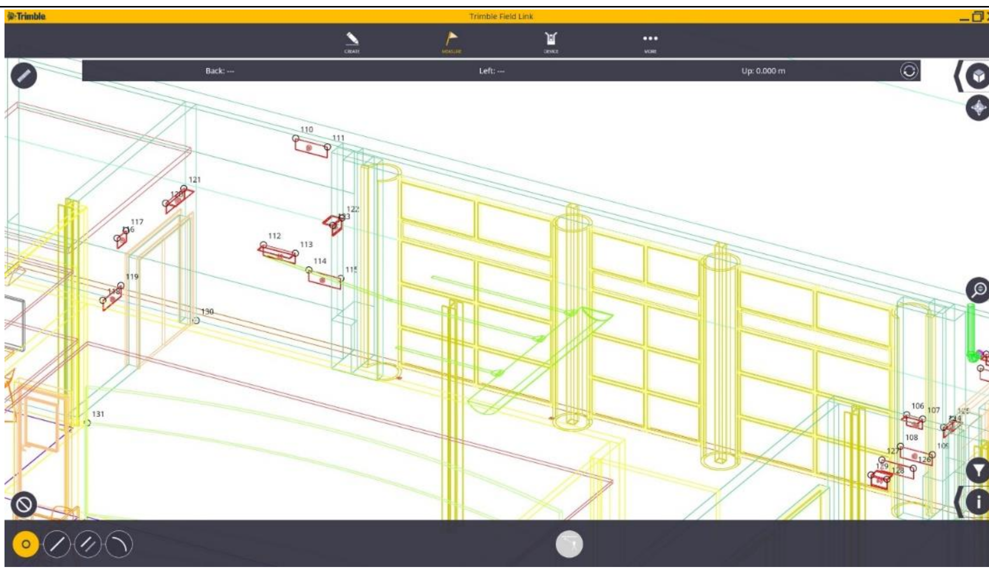

Fig. 4. Layout software used to locate templates (Trimble Field Link)

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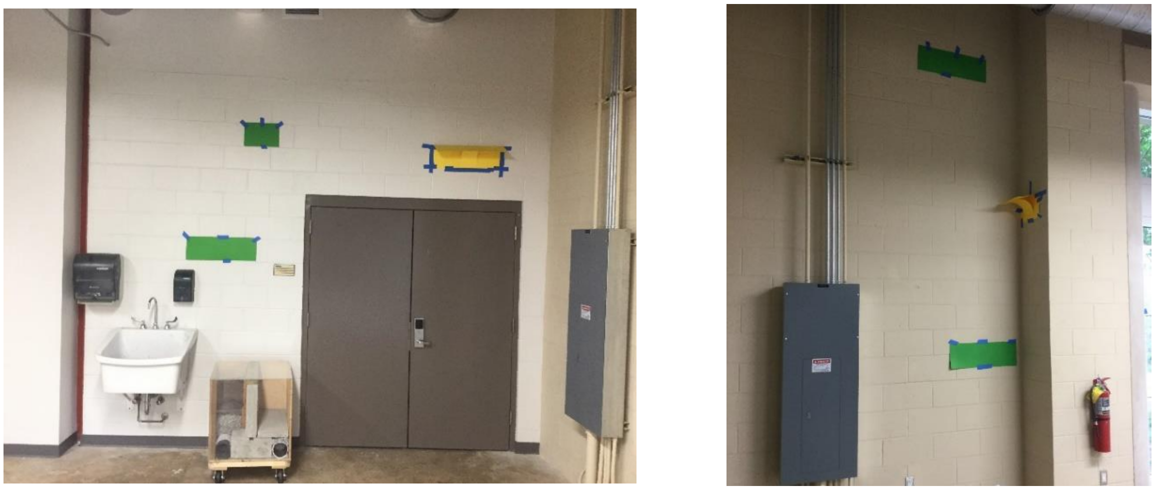

Fig. 5. Example of Embed Templates in Experimental Space

The test population consisted of 35 students some of whom went through the simulation with the lift drawings and some of whom went through the simulation with the Hololens and some of whom went through both exercises. Students were given approximately 6 minutes to complete their verification and inspections using both the 2D lift drawings and the Hololens. See figure 6 below images of the experiment process.

Fig.6. Experiment with Hololens and Lift Drawings Respectively

The hologram and the lift drawings contained 14 embeds which were supposed to be located and verified within a six minute time frame. Of the 14 embeds 3 were intentionally left out and not included, both the embeds that were included and those that were left out were to be spotted and verified by the test population. The same embed templates were used for both the hololens exercise and 2D lift drawing exercise. The results of this experiment are discussed and analysed below.

3. Results and Analysis

Of the 35 students who participated in this experiment 11 completed both the "lift drawing" exercise and the "hololens" exercise, and the remaining 24 students completed one or the other of the two exercises. The 2D lift drawing exercise was done primarily to serve as a control for the Hololens exercise to derive if there is any benefit in utilizing the Hololens for embed coordination and verification.

We had a total of 25 students participate in the lift drawing exercise, during that exercise they were given approximately 6 minutes to either locate and verify all 14 embeds and identify which ones were missing. As was stated prior by design 3 of the embeds were missing and 11 of the embeds were installed. The results of the student's participation and the numbers of errors that were made are seen in the chart below.

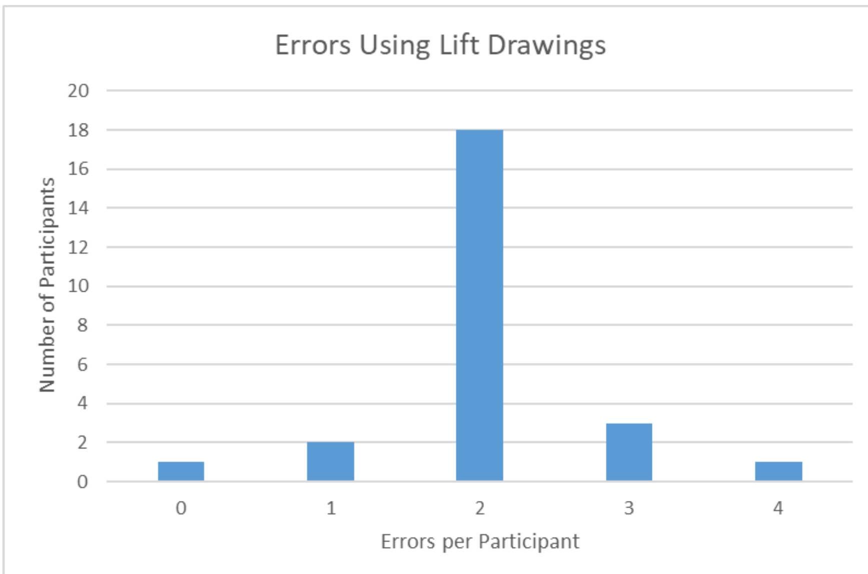

Fig. 7. Errors Using 2D Lift Drawings

As seen above the median for number of embeds that were not properly verified was 2 and the mean was calculated at 2.04. There were generally two types of errors that a participant could make 1. Failing to Verify Completed Work 2. Failing to identify embeds that were never placed or omitted.

The embeds which were missed most frequently using the lift drawings were embeds numbers 15 and 21. See the images of the model below in figure 9 which identifies those embeds. Their locations made it difficult for them to show up prominently on the "lift drawings."

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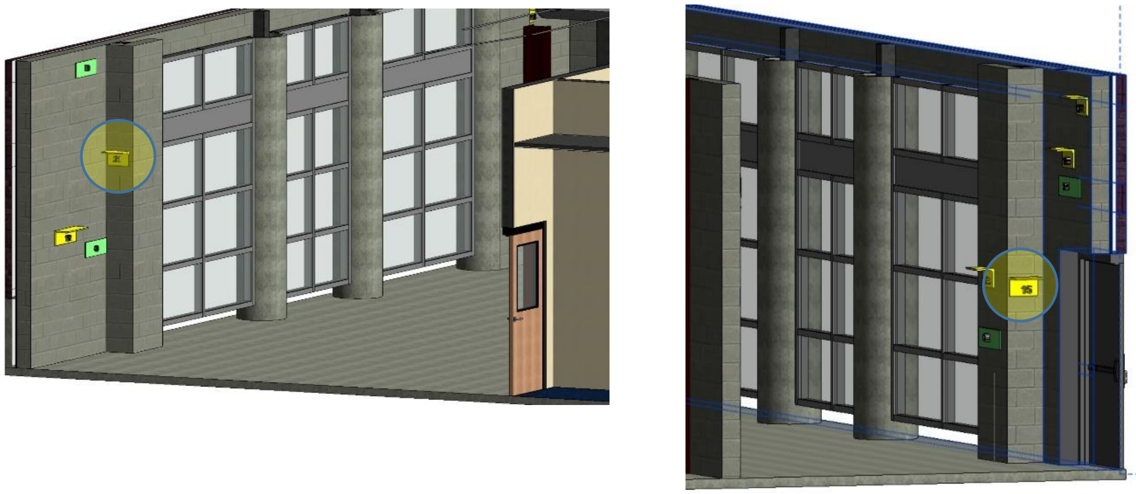

Fig. 9. Locations of Embeds which were most frequently missed with 2D lift drawings

We had a total of 21 students participate in the Hololens exercise, during that exercise they were given approximately 6 minutes to either verify or deny that all 14 embeds were either installed or missing. As was stated prior by design 3 of the embeds were missing and 11 of the embeds were installed. The results of the student's participation and the numbers of errors that were made are seen in figure 10 below.

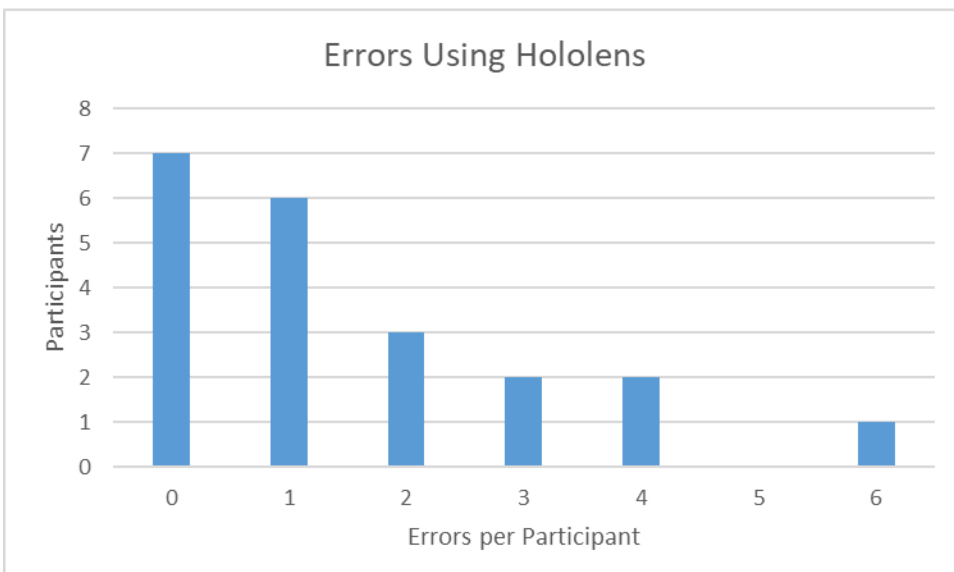

Fig. 10. Errors Using Hololens

As seen above the median for number of embeds that were not properly verified was 1 and the mean was calculated at 1.52. There were generally two types of errors that a participant could make 1. Failing to Verify Completed Work 2. Failing to identify embeds that were never placed or omitted.

4. Conclusions

During the course of this experiment it became clear that the Hololens showed promised for inspections and verification of concrete and masonry embedments. Although results appear to be somewhat preliminary we feel confident in the fact that the Hololens is an improvement over the "lift drawing' process in both time and precision. Time was not measured directly but it was a qualitative observation that the students who conducted the Hololens experiment finished significantly faster than those who participate in the 2D lift drawing control exercise. It also appeared that the Hololens allowed the students to better locate the embeds which would be traditionally hard to represent in 2D lift drawings. While drift and anchoring of the holograms were somewhat of an issue the technology was sufficient for accurate verification. While the technology was sufficient for verification and inspection it became clear that the technology still has some refinement to undergo before it is precise enough for installation and layout. After concluding this preliminary research on embed verification our data raised some new insights and questions that will be explored in future research.

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Using Dynamo for Model-Based Delivery of Facility Asset Data

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Abstract

Large facility owners are becoming increasingly aware of the value and advantage of utilizing design and build teams to capture and deliver facility asset data necessary to populate their Computerized Maintenance and Management System (CMMS) for efficient operation and maintenance of their facilities. Facility asset data can be delivered using various formats including a spreadsheet-based or a model-based deliverable. In a spreadsheet-based deliverable, asset data are captured and stored using a spreadsheet specifically formatted to allow the end user direct linking of the spreadsheet to the CMMS and automatic upload of the data. In a model-based deliverable, asset data is captured and loaded into a BIM model then transferred directly or indirectly from the model to the CMMS using various data exchange methods.

This paper discusses the indirect linking of facility asset data captured in a Revit BIM model to the facility management system through exporting the data to an external database. Dynamo, an open-source script-programming tool that works within the Revit environment, is used to extract and export the data from Revit to an external SQL database in a specific format and organizational structure that would allow for uploading of the data to the CMMS. Dynamo script (e.g. Python script) was used to export certain data parameters in a specific order and format. Exported asset data parameters and values are saved to the SQL database and linked to the CMMS to support operations and maintenance.

The paper uses a case study approach to illustrate the implementation of Dynamo to a renovation project for a large academic institution. Asset data for the project is captured from project plans and submittals and loaded into a Revit BIM model. The Dynamo script is tested to verify the export of data in the required format.

Peer-review under responsibility of the scientific committee of the Creative Construction Conference 2019.

Keywords: Asset data; Revit, Dynamo; SQL (standard query language); CMMS (computerized maintenance and management system)

1. Introduction

The capital facility industry continues to suffer from data inefficiencies. The fragmented nature of information exchange and management during design, construction and through facility management causes an estimated annual loss of $15.8 billion (USD) in the U.S. alone [1]. Efforts focusing on efficient processes and workflows that utilizes BIM continues to be developed to define specific owner needs, capture and transfer life cycle facility data to the owner's computerized maintenance and management systems (CMMS) [2, 3]. Yet research still recognizes that there continues to be gaps and challenges to directly link BIM to FM practices and systems used [4,5]. [6] Proposed a BIM-FM holistic process workflow to define, capture and transfer lifecycle data to a computerized maintenance management

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systems (CMMS). The proposed process comprises of six basic steps: identify need, specify data requirements, define format, define transfer mechanism, develop standards, and update CMMS database. The information needs analysis, data requirements, defined handover specifications and format were discussed as part of a case study [7].

Three main methods for data transfer were explored as part of the research investigation and include: (1) utilizing IFC models and schedule data exported to Navisworks and Data Tools to allow for an as-built federated model that can hold structured and unstructured data, (2) the use of the Archibus Extension in Revit to map parameters directly into Archibus, and (3) developing custom script programming within Dynamo to export Revit parameters and required data into the required format so it can be directly imported into the CMMS, AiM. The Navisworks process, though allowing for a complete model with links to structured and unstructured data still required manual manipulation of exported spreadsheet data to transfer to the CMMS. The Archibus Extension option provided a valuable insight but was deemed by the owner to not be a viable option because it would require them to switch to Archibus to manage all facilities.

This paper summarizes the process of using Dynamo to export data from the BIM model (Revit) to an external *.csv* file. This data file can be converted to an Excel file format or linked to an SQL database to transfer the captured facility information to the CMMS.

2. Case study overview

The case study project consisted of the renovation of mechanical and electrical systems for a 35,000 sqft science and research facility building in an academic institution. Table 1 summarizes asset group information for the project. Asset group name abbreviations used by the academic institution are adopted from the US CAD Standard. Table 2 summarizes twenty (20) pieces of equipment assets captured that are required by the owner to track and maintain. Equipment names are listed as it appear in the plans. Table 2 also shows the parent/child relationship, and the floor/room where each equipment is located.

Table 1. Asset groups considered in the science building renovation.

Asset Group	Description	Asset Quantity	Mechanical	Electrical
AHU	Air Handling Unit	2	X	
ERU	Energy Recovery Unit	1	X	
FAN	Fan	4	X	
FCU	Fan Coil Unit	9	X	
HTR	Heater	4	X	
HUD	Humidifier	1	X	
P	Pumps	4	X	
SEP	Separator	2	X	
TNK	External Tank	2	X	
EMER-ATS	Emergency Transfer Switch	2		X
EMER-GEN	Emergency Generator	1		X

Table 2. Equipment general information.

Asset Group	Equipment Name	Parent	Location
AHU	MAU-1 (Supply Air Handler)		Roof
AHU	EAU-1 (Exhaust Air Handler)		Roof
ERU	Energy Recovery Unit	EAU-1	Roof
FAN	Supply Fan	MAU-1	Roof
FAN	Exhaust Fan	EAU-1	Roof
FAN	F-1		Basement – Mech/Elec Rm 7
FAN	F-2	ERU	Roof
FCU	FC-1 through FC-8		Main Floor
FCU	FC-9		Basement
HTR	HUH-1		Basement – Mech/Elec Rm 7
HTR	ECH-1	ERU	Roof
HTR	ECH-2, ECH-3, ECH-4	MAU-1	Roof
HUD	HUM	MAU-1	Roof
P	HWP-1, HWP-2		Basement – Mech/Elec Rm 7
P	ERP-1	ERU	Roof
P	CWP-1		Basement – Mech/Elec Rm 7
SEP	AS-1		Basement – Mech/Elec Rm 7

SEP	AS-2	ERU	Roof
EMER-ATS	ATS-1, ATS-2		Basement – Mech. Equip. Rm
EMER-GEN	Emergency Generator		Basement – Mech. Equip. Rm

Each asset group has common and specific attributes required for managing and maintaining the asset post-construction. Common attributes are properties that are similar across the different asset groups. , Specific attributes are unique to the asset group. [7] Discussed the institution's classification and definition of asset attributes and how they support facility management activities.

Common attributes comprises of twenty two (22) properties such as ASSET_TAG, ASSET_GROUP, MANUFACTURE _CODE, MANU_PART_NUMBER, SERIAL NUMBER, WARR_DATE_FR, etc. Specific attributes vary in number for each asset group. Table 3 provides an example of specific attributes for the AHU (Air Handling Unit) asset group.

Table 3. Specific asset attributes for AHU (Air Handler Unit) asset group

	AHU Common Attribute	
Bas Point Address	Min. Outside Air	Economizer
Heating Source	Max. Outside Air	Economizer Type
Heating Capacity	Cooling Source	Total Static Pressure
Total Air Flow	Total Cooling Capacity	Type
External Static Pressure	Sensible Cooling Cap	

2.1 Case study model

The renovation project did not have a 3D model available. For the purposes of this research, three (3) basic 3D Revit component models were created: Architecture, Mechanical, and Electrical. The basic wall and room configurations for the spaces involved in the renovation were modeled in the architecture model. Only the assets that were under renovation were added to the mechanical and electrical models. As shown in Figure 1, Both the mechanical and electrical models were separately linked to the architecture model to allow for viewing their respective elements within the context of space and rooms defined in the architecture model. Once parameters and data were loaded into the mechanical and electrical models, the three models were linked together as an overlay reference using "Manage Link" in Revit. The purpose of developing three separate component models was to replicate the process of a typical project where each discipline consultant or trade contractor develop their own model.

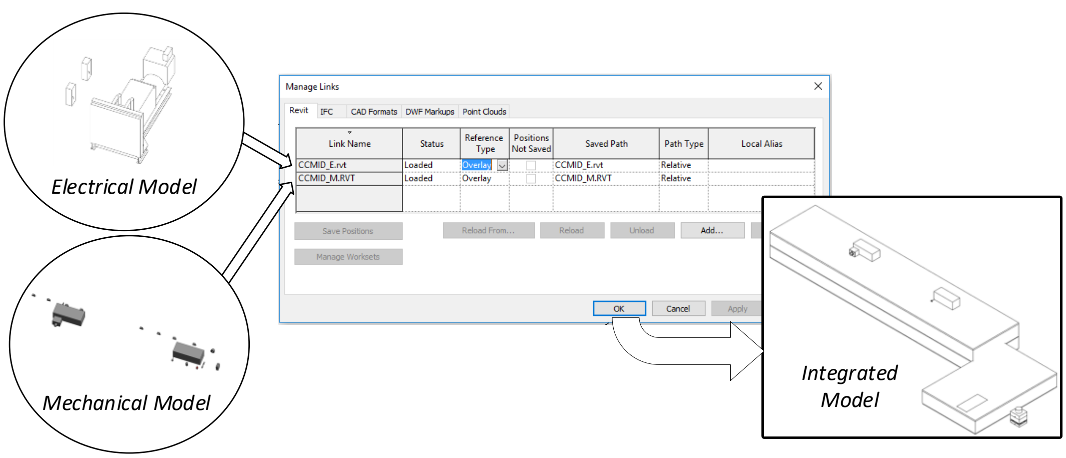

Fig. 1. Linking the mechanical and electrical models to the architecture model.

Within each of the mechanical and electrical component models, stand-alone elements that did not have a parent-child relationship (e.g. boilers or fan coil units) were easily modeled from standard Revit family libraries. Elements that include other elements as an assembly with parent-child relationships, such as Air Handling Units (AHU) or Energy Recovery Units (ERU) with fans, had to be modeled such that it graphically appeared as an assembly and, at the same time, it allowed to define parameters for the assembly independent from the components. Modeling these elements as

Revit Assemblies were first considered. All components of an assembly were selected and combined using the Revit assembly tool to create the assembly as shown in Figure 2. This allowed assemblies such as AHU and its components to appear graphically correct and have their own independent parameters; parameters for the assembly and parameters for the components within the assembly (e.g. Return Fan). However, Revit does not distinguish between different assemblies and therefore it does allow for defining customizable parameters for two different assembly types. For example, an AHU assembly and an ERU assembly cannot have their own independent set of parameters assigned to them. Any unique parameter assigned to the AHU assembly through the parameter assignment process will be automatically assigned to all other assembly types defined in the model.

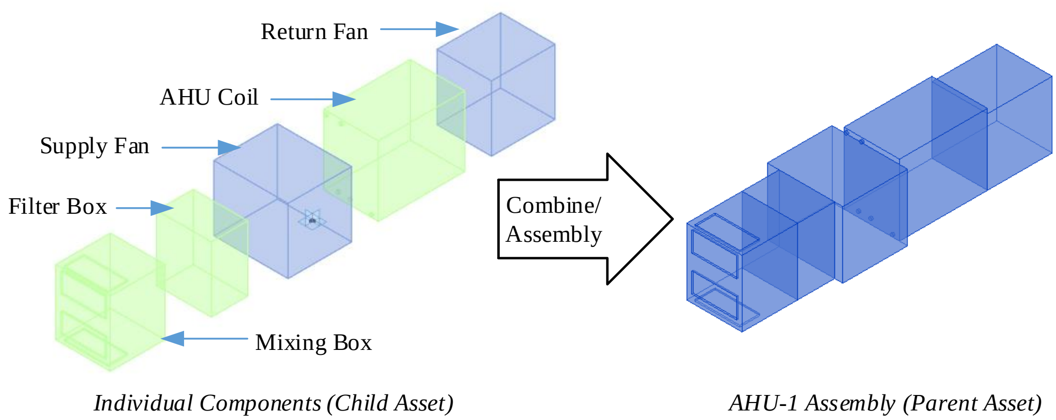

Fig. 2. Creating parent assembly by combing individual components in Revit.

An alternative solution was to use nested families. Families of components of an AHU shown in Figure 2, such as Filter Box, Supply Fan and so on, would be nested to another host component family such as Return Fan to create a group of nested components. Graphically this would accurately represent an assembly and components, however, there are issues with defining parameters of individual components nested to a host component; they do not translate through the host. Parameters of nested components need to be identified through the host element and would not be associated with the individual components.

Finally, though not graphically the best option, families representing the different components of were modeled in the same geometric space representing the assembly as shown in Figure 3. For example, a non-descript block is modeled to represent the location and size of an energy recovery unit (ERU) assembly. This modeled object can then support the attributes and parameters associated with the ERU as the parent asset group. Within the same space, families for detailed components such as fans, pumps, heaters, etc., were placed in the model. Each component being their own family were able to hold the parameters of the child asset.

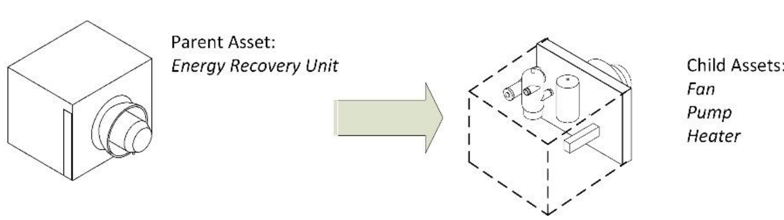

Fig. 3. Modeling parent-child components in Revit.

2.2 Populating model with required asset attributes and data

To load the common and specific attributes into the mechanical and electrical Revit models, a shared parameter file was created using the Shared Parameter Manager™ module (BIM Management Suite), a 3rd party plugin for Revit from CTC (www.ctcexpresstools.com). CTC BIM Management Suite contains add-ons that work within Revit's modeling environment to help manage data. The Shared Parameter Manager™ allows the user to easily create and group parameters and load them into the Revit model. The user can then apply the parameters to the appropriate categories, families and assemblies of objects. The plugin is much more robust than using the standard Revit tools to define parameters and allows for batch loading and assigning data to the Revit objects, saving time and minimizing errors. To input parameter values to the different elements in the model, the Spreadsheet LinkTM module of the CTC BIM Project Suite was used. Specific categories and parameters are identified within the Spreadsheet Link tool by the user. The user can then enter the values for the parameters within the tool in a user friendly and familiar spreadsheet view. This allows for quick and efficient entry of the data. As soon as it is entered and input into the Spreadsheet Link tool the parameter is updated in the model. The process for loading the shared parameters into the model and inputting values into the model was discussed in further detail in a prior stage of the research [9].

Once parameters and data are loaded into the mechanical and electrical models, a single 'Integrated' or group model was created with all the parameters and data attached. This four (4) step process is summarized in Figure 4.

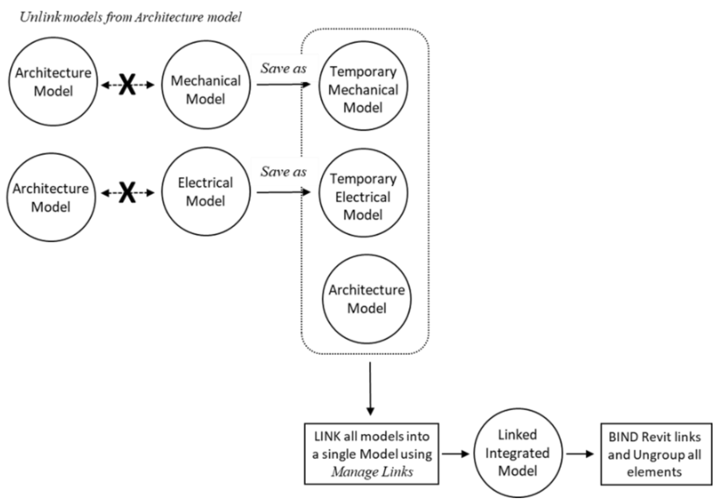

Fig. 4. Linking and binding component models to create an integrated model.

3. Capturing and exporting model data using Dynamo

To transfer the asset data captured in the BIM model to the CMMS platform used by the academic institution, the data had to first be exported to a .csv (Comma Delimited Spreadsheet) file that is then linked to the CMMS. had to export specific format for that data is required. The .csv spreadsheet file must be structured in a specific format to allow the CMMS to recognize the data embedded in the file. The spreadsheet file comprised of six (6) sheets defined in the order listed below:

1. General: lists general properties for each asset.
2. Attribute: lists specific attributes for each asset.
3. Parts: lists replacement part(s) number and quantity.
4. Warranty: lists asset warranty information (description, start and finish dates).
5. Locations Served: lists the locations served by the asset and corresponding usage factor (%) of asset.
6. Classification: Omniclass and Master Format classification numbers for each asset.

The overall process for the Dynamo script is shown in Figure 5 is completed in four (4) main steps. First, data in the "General", "Parts", "Location", "Warranty", and "Classification" tabs are queried, captured and exported (steps 1, 2, and 3). Second, data in the "Attributes" tab (steps 1, 4, and 3) are queried, captured, processed then exported. The reason the "attributes" tab is processed separately is because the format of the data in that sheet (tab) is structured differently than the other tabs; hence requires additional code.

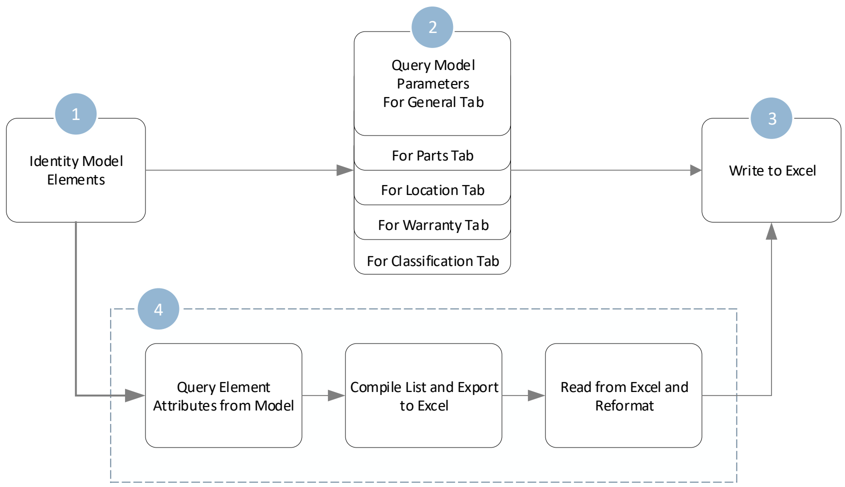

Fig. 5. Dynamo script workflow.

The following two sub-sections provide examples of the Dynamo script used in steps 1 and 2 in Figure 5 above.

3.1 Identify model elements (step-1)

Figure 7 illustrates step-1 script required to identify all model elements under the different asset groups required under this study and need to be tracked (total of 22 elements). The script in Figure 6 shows three (3) main sub-steps:

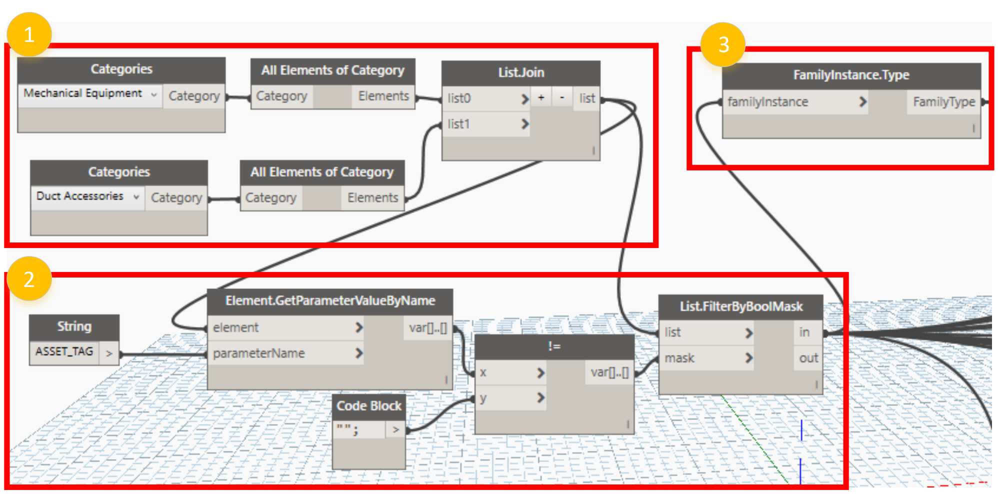

Fig. 6. Identifying model elements.

1.1 The nodes "Categories" and "All Elements of Category" access all the family instances of a particular category. For the test case, Mechanical Equipment and Duct Accessories were the category names within Revit that contain all the assets that are being tracked. The "List.Join" node compiles lists from each of the inputs that can be queried in future parts of the process. The "All Elements of Category" identifies all elements in the model of the specified categories.

1.2 To limit the elements in the list, the parameter "ASSET_TAG" is checked for those assets that have a value. As part of the data documentation and model creation phase, every asset that is being tracked is provided an ASSET_TAG at the time of creation so it can be tracked. The "Element.GetParameterValueByName" and "!=" nodes allow for filtering the list. The Element.GetParameterValueByName outputs a list of ASSET_TAG values. The != node is then used to compare the output list of variables (the X input) to a specific value (Y input). The Y input in this case is set to null ("";), or an empty string. The List.FilterByBoolMask compares the two lists of

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elements and masks the elements that have a null value for the parameter. The result is a list of only the elements that have a defined asset tag.

1.3 The resulting list from the List.FilterByBoolMask can be used to identify parameter values of a specific element but does not work on type parameters. The FamilyInstance.Type node is used to identify the type parameters of the element. This is required for identifying parameters that are assigned to the element type, such as the “ASSET_GROUP”.

3.2 Querying model parameters (step-2)

The objective of the script for step-2 shown in Figure 7 is to query model parameters in the “General”, “Parts”, “Location”, “Warranty”, and “Classification” tabs and create appropriate lists of those values that can be written to the .CSV file (completed later in step-3). The script in Figure 8 shows two (2) main sub-steps:

2.1 Identify the values of specific parameters for each tracked element. The “Element.GetParamaterValueByName“ node utilizes two inputs. Depending on the parameter type the “element” input is a list. The “ParameterName” input is a string of the parameter’s name. The result is an indexed list of all parameters of the queried elements.

2.2 Each output of the “Element.GetParameterValueByName” node is then added to a list using the “List.Create” node. These are created by the tab of the csv spreadsheet and organized in the required order.

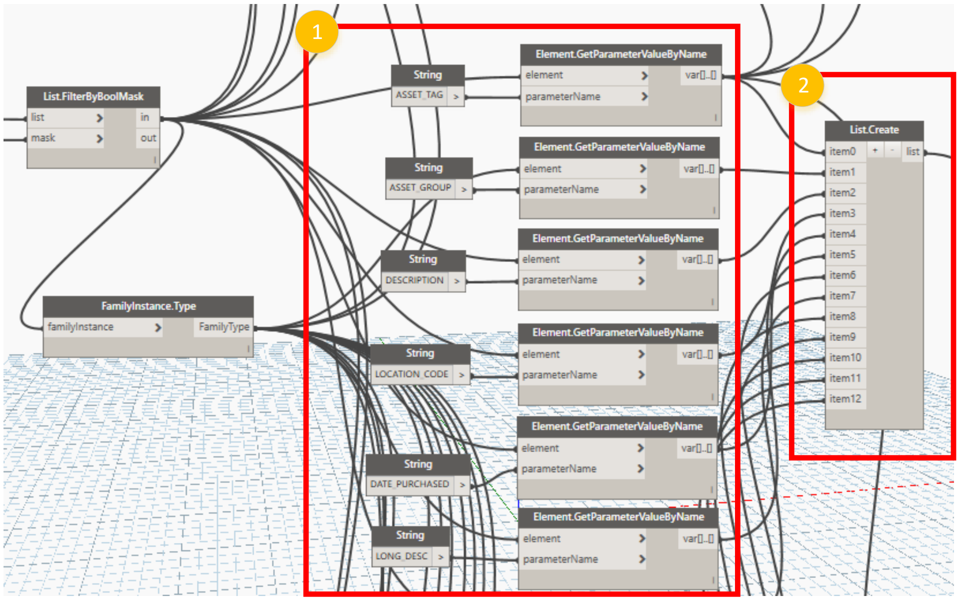

Fig. 7. Identifying parameter values.

4. Conclusion

The developed process allows for collecting facility management related date throughout the project lifecycle within ta Revit model and automating the process of exporting that data for use during facility management. The process helps the owner address the issues of timeliness and efficiency of information transfer to make data usable at the end of the construction process. The data exported through this process can be directly imported into the current CMMS system of the owner. This process replaces a tedious manual process and cuts down on time and potential for error during the data transfer process.

To validate the developed process the output spreadsheet was checked for usability with the CMMS and compared to a manually developed spreadsheet. The data values that were extracted were validated as correct and extraction process took a fraction of the time to complete.

At this time, a limitation exists in that the designed Dynamo approach only allows for data transfer in one direction. Data is extracted from the BIM model and is used to update the CMMS however data changed in the CMMS is not reflected back into the BIM. This would have to be done manually or through further developing the coding. The authors believe that additional development can allow the data exchange process to be bi-directional and will explore it as part of future research. Future research will examine the utilization of a SQL database and Dyanmo programming to serve as a bidirectional link between Revit and the CMMS. SQL will remove a current manual step of importing the spreadsheet as the CMMS works directly off a SQL database. This will require slight programming change but allow for maintaining the geometric representation of the building with updated asset information. This would also serve as a continuous record. This can also then link to other unstructured data into the model such as owner's manuals and relevant PDFs. These forms of unstructured data are not currently addressed in the developed process. The current development is also limited to the current assets that were used in the case study, however, the framework for extraction can be used to quickly add additional assets that the facility owner will be tracking.

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Using UAV's and BIM integration to improve infrastructure delivery – A case of Gauteng department of Infrastructure Development, South Africa

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Abstract

Meeting planned timelines, quality and budget requirements in construction projects is always a challenge and the impact means that resources that should be used in other development projects get re-directed to addressing the problems created by exceeding time, quality and cost aberrations. However, the fourth industrial revolution has not spared the construction industry and it is affecting the way infrastructure is delivered. According to the World Economic Forum, digital technologies have begun to change how infrastructure and the built assets are designed, constructed, operated and maintained. The entry of technology to the industry is also driven by the realization that in order to improve on the delivery of projects, adoption of innovative methods that are based on digital technology is essential as it ensures efficiency and effectiveness in project management, transparency, and record keeping. In this study, we report on the use of drones (Unmanned Aerial Vehicles - UAV) to capture site data and how it was integrated to Building Information Modelling (BIM) models to produce as-built drawings and quality checks from comparisons with as-imagined models. Data used in the study was obtained from construction projects sponsored by the Gauteng department of infrastructure, in South Africa. Findings demonstrate that UAV and BIM technology has the potential to improve the efficiency and effectiveness of project delivery. An enhancement in monitoring of work progress during construction, site surveillance, and integration of transformed 3D models to BIM to achieve more effective project management, record keeping, and quality control were observed. The accuracy of the data was also found to be adequate for the purpose of project management tasks.

Keywords: BIM; CPM; Drones, Integration management; South Africa; UAV

1. Introduction

Unmanned Aerial Vehicles (UAV) had its first application in military use in the United States in times of civil war, however with recent advancement in technology the applications have broadened and now allow for civilian use. The introduction of Drone technology (UAV) has multiple uses including; Real Estate and Construction monitoring, Agriculture monitoring, Remote sensing, Commercial Aerial Surveillance, Film Making, Gas, Oil and Mineral exploration, Mapping, Relief efforts, Recreational use and a host of various other activities the mind can conceive.

UAV's in the construction industry assist Clients, Contractors and Consultants in various circumstances, namely; Progress Monitoring, Site planning, Error Resolution, Inspections, Safety and risk assessments, Aerial photography, Site and Building survey etc. The above uses, going forward in the construction industry are critical for projects of all

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sizes in the various aspects. The images and video footage also provide a method of recording critical stages in a project for further review and much later to find root cause of problems. Notwithstanding the rich data received from UAV's, it must be understood that this data does not stand alone and is more powerful when integrated with BIM solutions. UAV data integration with BIM assists in critical analysis of projects and allows for comparison between information on paper and the built product, allowing valuable decisions to be made in time and therefore negating the various risks. Noting the tremendous applications of UAV's in the construction industry, it is of utmost importance that the data is correctly interpreted to form a critical understanding of the various data sets captured from UAV's.

The Gauteng Department of Infrastructure Development (GDID) is a large organization that is tasked with delivering infrastructure projects for the South African Government in the context of the smallest but most productive province, Gauteng. On an average year, the GDID is responsible for managing, executing and delivering over three hundred infrastructure projects ranging from small schools to large hospitals. It is in this context, that the GDID promulgated the use of drone technology to monitor and manage their projects.

It was realized that in order to achieve superior results from the project monitoring exercises, appropriate tools were necessary especially that ensuring projects meet the cost, schedule and quality objectives is the goal of monitoring [7]. Consequently, the method of monitoring determines project performance. Until now traditional monitoring tools and methods have not succeeded in ensuring that projects meet their objectives and therefore project aberrations are commonplace.

This paper reports on experiences from the use of UAV in the construction industry, more especially in the fields of monitoring, management and quality control of South Africa's public sector infrastructure projects. Together with UAV Technology, the authors integrate Building Information Modelling to critically analyse infrastructure projects in terms of accuracy, quality, material usage, programme and project management. The research yielded some exciting results which are shared in this paper; however, the authors seek to determine other uses and further research going forward.

2. Literature review

In this section, the authors review various sources of literature to form a theoretical framework in which UAV technology operates. This section will open with a brief overview of what UAV technology is and further delve into the uses of UAV technology in the construction industry.

2.1. What is UAV Technology?

The term UAV refers to an aircraft that is not manned physically by a pilot but works through human involvement [6]. An Unmanned Aerial Vehicle or Drone is a technology that requires an aircraft system, i.e. multi rotor drones, fixed wing drones, single rotor helicopter, fixed wing hybrid, quadcopter among others. and a control system to operate the aircraft remotely [13]. The first uses of drones appeared for military use, but have now come with many civilian and professional use in the recent years [12]. UAV's have become a very popular tool in the construction industry as the uses far outweigh many traditional methods of reporting, monitoring, inspecting etc. [9]. Due to the ability to video record and capture photographs with geographic coordinates (X, Y, Z coordinates), UAV technologies assist in many other ways for namely; capture of objects and creation of a point cloud, accurate measuring of objects in 3D, surveying etc. [11]. Drones have incredible ability and more avenues are being opened on an ongoing basis due to software improvements, new hardware and technology etc., however what solutions does this allow for in the construction industry?

2.2. UAV uses in Construction

Among the various uses of UAV's, the construction industry has found some nifty uses. In this section the authors explore the various uses of UAV's associated with the construction sector.

2.2.1 Land Surveying

For many years, the construction industry relied heavily on professional land surveyors to perform topographical surveys. In recent years, UAV technology has entered this space allowing consultants, clients and contractors to perform topographical surveys more often using UAV's. A surveyor is still required for professional responsibilities, however UAV's assist with quick on the go information only surveys, reducing the cost of hiring a surveyor [2]. The information extracted from a UAV survey is also near accurate with a satisfactory error of between 1cm for ground control points and 4cm for other parts of the survey [10].

2.2.2 Site Inspections

Site inspections form a part of the ongoing process of construction. With the introduction of UAV's, this has made it easier to inspect hard to reach areas of buildings [1]. All parties involved in the construction of infrastructure are seeing the benefits of UAV inspections from contractor to clients and most importantly the consultants. There is a move from manual based inspections to automated, intelligent processes that can keep record of works on site from day one [3]. The ability to have autonomous control makes UAV's easy to use and allows for inspections to be carried out more accurately [4]. From the various views on various authors, it is evident that UAV's are changing how inspections are carried out in the construction industry.

2.2.2 Project Management

UAV's in the construction management sector has been slow on the initial uptake, furthermore the concept is not well understood in this sector [5]. However, Zhou *et al* [14] argue that various academics have delved into the field of construction project management in sectors such as safety inspections, 3D modeling, aerial construction etc. UAV's can be used for various tasks, but more especially for the monitoring of progress on construction sites. This allows the project manager to have an idea of updated work on site at various time intervals, even daily if one needed it [8]. It is important for UAV technology to be adopted into the construction project management realm; further research needs to be conducted in this area to understand the benefits.

The authors of this research have concentrated primarily on three topics with reference to UAV's in the construction industry. This has been specifically coordinated as such to narrow the focus of this research.

3. Research Methods

This research aims to discover the benefits of UAV's and BIM on public infrastructure projects. The authors adopted the following research method.

3.1 Task 1: Review of Literature

In this task, the authors conduct an extensive and critical review of literature of; UAV definition and various uses of UAV's in the construction industry.

3.2 Task 2: Research Methods

The study took a case study approach and documents to evaluate the potential use of Unmanned Aerial Vehicles (UAV) and Building Information Modelling (BIM) to enhance project delivery. The UAV's and BIM were used to capture site data and as a basis for as-built and as-imagined/designed comparisons in construction projects. For the study, the construction of a government clinic in Gauteng was used as the case. Observations of what was achieved as well as feedback from the study team on the potential and value of using the UAV's and BIM were solicited and analysed to inform the study.

3.3 Task 3: Analysis of Data

The analysis of data for this research is by far the most important aspect of this paper. Although a case study approach was used, the analysis of data was made possible by an online drone mapping software. The authors found PIX4D to be the most appropriate software to analyse the data captured by the drone. The data from the drone was provided by the GDID and their in-house drone pilots, however the research team assisted in recommending techniques for best practices. The following best practices were recommended:

3.3.1 Many photos must be captured by the drone, nothing less than 500 photos for best results

3.3.2 The UAV must capture photos from a height of not more than 50m, this allowed for detailed high-resolution images.

3.3.3 Create a large overlap of photos by at least 75%.

With the three best practice techniques applied, the research team sort to process and analyse the data received. Data was processed using PIX4D which created various types of outputs namely; Orthomosaic map (2D), Point Cloud (3D) and 3D textured mesh (3D). The Orthomosaic map was used to compare 2D data, i.e. overlays, CAD matching etc. which allowed the researchers to compare what was envisioned with what was currently being built on site. The point cloud data was integrated into Revit Architecture 2019 for as-built modelling and quantity take off, this was done so that in future it can be an accepted method of cross checking for payment certificates. The 3D textured mesh was used to measure materials on site and for inspection. The textured mesh is a much clearer version of the processed 3D model and allows for an in-depth inspection of various elements of the building. In the next section the authors discuss their findings of the research using the above-mentioned research and analysis techniques.

4. Findings

Findings from the initial concept have shown that UAV and BIM technology can be used for efficient and accurate site data collection, monitoring of work progress during construction, site surveillance, and integration of transformed 3D models to BIM or 2D CAD overlay over the UAV output to achieve more effective project management, record keeping and quality control. These aspects of the findings are presented below.

4.1 Virtual Site Inspections

Observations from the project team's comments indicated that the outputs from the integrated 3D models enabled inspection of the entire construction site of a government clinic much more closely than would ordinarily have been achieved with traditional inspection methods. Traditional methods of inspections afford few project team members an opportunity to inspect the constructed works more closely especially on areas that require climbing namely; roof tops, suspended slabs, beams etc. Our observation from the proof of concept, were that the methodology of using UAVs gave the entire professional project team including the client representatives, an opportunity to inspect difficult-to-access areas such as rooftops, excavations etc. The images below were processed using PIX4D and made use of 3D textured map.

(a) (b)

Fig. 1. (a) 2D View of slab to be inspected; (b) 3D View of slab to be inspected

4.2 Accuracy checking and as-builts

The UAV output was also found to be useful for quality control purposes. The 2D CAD overlay on the UAV point cloud output revealed discrepancies between design and as built. Discrepancies included deviations from the specified measurements, increase or decrease in scope of work, and the study team was able to red flag these issues for further follow-up. The study team further observed that benefits from using the UAV output together with the BIM models, was the potential of generating the as-built drawings or models of the facilities under construction. Production of as-built drawings is one of the neglected aspects of the project especially in Africa.

(a)

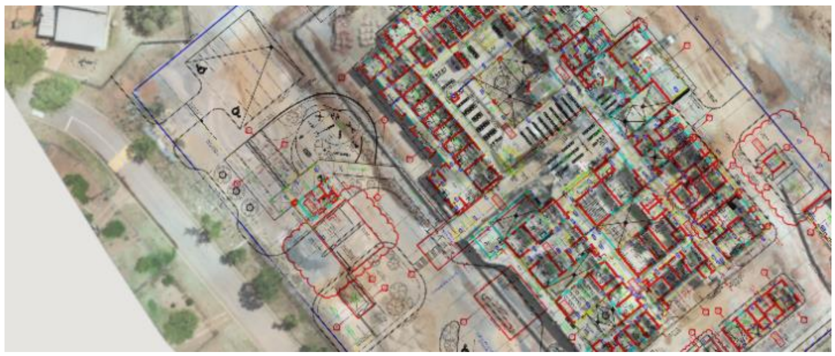


Fig. 2. (a) CAD overlay applied over Orthomosaic map

4.3 Project Management and Quality control

Accessing and retrieval of information relative to progress and quality control was found to be easier. Equally, the study participants expressed optimism in the methodology eliminating disputes when it comes to claims. The generated 3D models enabled clear visualisation of the building under construction and thereby enabling description of project status with ease. Orthomosaic 2D images allowed for side by side comparisons and this could be used as proof of works executed. From the below images, it is evident that UAV's can truly allow for distance working and virtual visits to sites. Furthermore, projects can now have visual tracking with Realtime data available at will.

(a) (b) (c)

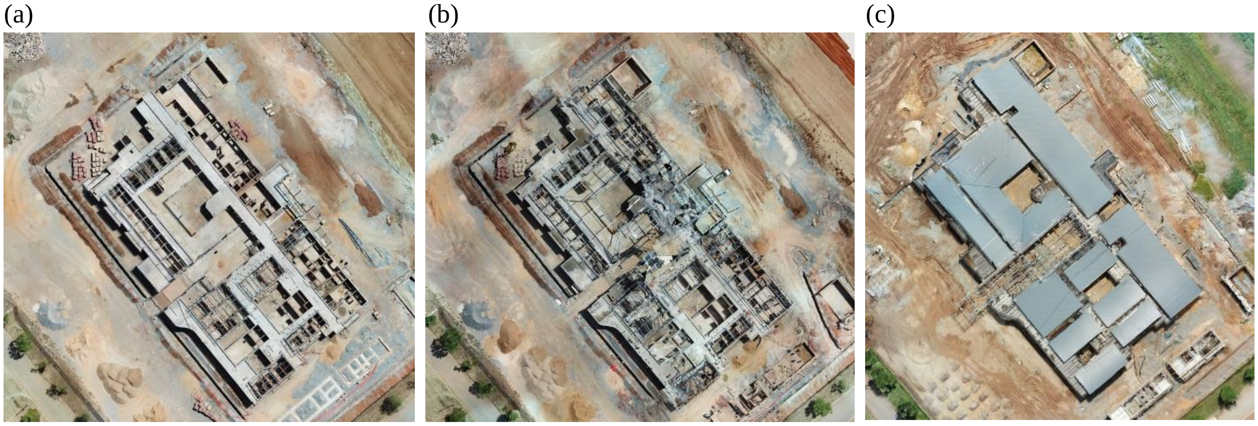


Fig. 3. (a) UAV Orthomosaic 18/10/18 (b) UAV Orthomosaic 27/10/18 (c) UAV Orthomosaic 14/11/18

4.3 Live measuring and BIM integration

By far, one of the more interesting and information bearing parts of this research included live measuring of materials on site and integration with BIM to measure quantities. In the first part the authors used PIX4D to measure quantities of soil and other building materials. This is an important method to determine materials on site. By using 400 images, a point cloud and textured 3D mesh was created for the purposes of exploring and measuring. The data was analyzed using the desktop version of PIX4D, which the authors found to be intuitive and easy to use. Referring to Fig. 4 (a), one can see the measurement of a heap of plastering sand which has been measured. This shows the possibility to measure quantities in a 3-dimensional form, which is accurate and can determine volume. Fig. 4 (b) shows a stack of bricks that can be measured using just a visual estimation. Further to just visual measuring, the creation of a 3D model enables the user to rotate and pan to view the entire site and capture all measured work. This method is powerful and can potentially reduce error and assist with speed and also reduce the need to be physically on site.

(a) (b)

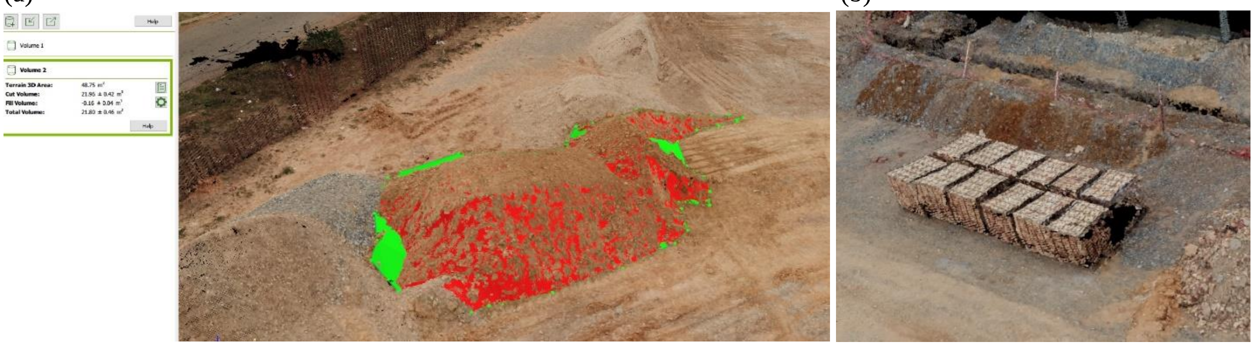
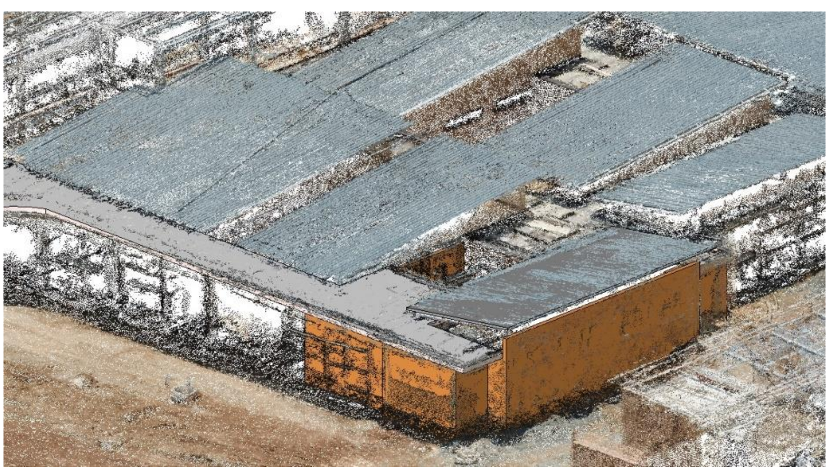


Fig. 4. (a) 3D Measurement of plastering sand on site. (b) Stack of bricks measured visually.

The use of measurement tools in BIM or from the mapper on the point clouds, was used to extract measurements to determine, the amount of work that had been done. BIM is used as a tool to measure quantities such as walls, slabs, roofs etc. The authors found that this was an accurate method to measure building elements. For the purposes of this research, the authors illustrate a small example of this method. A point cloud created in PIX4D was imported into Revit 2019 for use. Revit wall elements were traced from the point cloud as seen in Fig. 5 (a), thereafter a wall schedule was created within Revit 2019 to determine the drawn walls. Revit computed the total area of drawn walls as shown in Fig. 5(b). This method has proved that it is indeed possible to use UAV data and BIM to create a measured drawing that is accurate and live.

(a) (b)



<Wall Schedule>

A	B
Type	Area
230mm FACEBRICK	
230mm FACEBRICK	60 m²
230mm FACEBRICK	5 m²
230mm FACEBRICK	8 m²
230mm FACEBRICK	16 m²
230mm FACEBRICK	2 m²
230mm FACEBRICK	20 m²
230mm FACEBRICK	38 m²
230mm FACEBRICK	7 m²
230mm FACEBRICK	14 m²
Grand total: 9	170 m²

Fig. 5. (a) Walls traced from Point Cloud in Revit 2019 (b) Wall schedule with total area calculated.

5. Discussion and conclusions

Findings showed that potential existed in the use of UAV – BIM integration from production of design plans, monitoring of materials on site and measuring actual work done on site. Integration of UAV and BIM technology leverages the capabilities and opportunities that the fourth industrial revolution (4IR) has provided. We can now digitalise and automate many processes and outputs in the construction process for the benefit of our industry. Therefore, the use of UAVs (Drones) and BIM technology will bring accountability and transparency in Government projects, as well as reduce the many aberrations that occur in construction projects.

The use of drones to monitor the quality and technical aspects of a project is a breakthrough for the construction industry especially if multiple projects are being run at the same time. Drones are capable of reaching hard to access spaces on construction sites. From a safety point of view, a drone mitigates the risk of injury to all parties concerned. Reports can be easily generated from the drone footage by all parties concerned.

Annual quality inspections can also be performed by a drone for the maintenance of a project long after construction is completed. A yearly 3D model can be created to monitor deterioration of the structure and methods can be implemented to maintain the building accordingly.

Benefits of sharing the drone data with clients is evident as they can see their investment progress with quality on a weekly basis without having to visit the site regularly, especially if clients are far away from the construction site.

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