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AN AUTOMATED SEMANTIC SEGMENTATION-FREE APPROACH TO POINT CLOUD SCENE UNDERSTANDING IN CONSTRUCTION

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Abstract
It has been long shown that deep learning methods need voluminous training data to automatically process point clouds and develop accurate as-built construction models. On the other hand, conventional semantic segmentation of point clouds can be used but requires significant time and manual effort. In construction, public and private Building Information Model (BIM) databases are available as information source and can facilitate semantic registration and enrichment. Therefore, this paper takes the initial steps and advances the Derivative-Free Optimization-based (DFO) approach by automatically recognizing 3D objects from point clouds using available BIM data and registering the correlated semantic information to each detected object using geometry and color features. More specifically, the proposed framework takes the as-designed BIM models and point clouds as input, samples as-designed models, and registers information as a log text file to the generated point cloud by minimizing the Mean Squared Error (MSE) value using geometry and color features. In order to validate the proposed framework, preliminary experiments were conducted on an office point cloud taken from the Stanford 2D-3D dataset. Results highlighted the potential of the proposed DFO approach in making good use of available BIM resources to efficiently process point clouds and generate accurate and semantically enriched as-built models.

Keywords: as-built, BIM, derivative-free optimization, point cloud, semantic registration.

1. Introduction and Background

Construction scene understanding has long been attracting attention in the Architecture, Engineering, and Construction (AEC) industry. This has been done using point cloud measurement that represents rich geometry input data about the construction scene [1]. In addition, enriching geometries with semantic information can further enhance scene understanding [2]. As such, making use of Building Information Modeling (BIM) as a source of information to semantically enrich generated geometry could help in numerous construction applications.

Semantic segmentation is a process of assigning each point in the point cloud to its associated label. According to [3], semantic segmentation algorithms have two categories; rule-based or traditional and deep learning methods. Previous research defined the practices that extract hand-crafted features or models and then train classifiers as conventional. One of the first examples of traditional segmentation, presented in [4], used random decision forests to address dense semantic 3D scene understanding of indoor scenes. Another example introduced Markov Random Field-based approach for segmenting textured meshes into urban classes [5]. On the other hand, deep learning techniques have been employed to segment point clouds of building interiors [6]. Other research efforts [7] used convolutional neural networks to semantically segment point clouds of structural and mechanical components. Nonetheless, these methods are error-prone and limited due to the presence of various systems and objects in the construction environment as well as complex and dynamic context and applications.

Many studies exist in the literature on how to extract and utilize semantic information such as BIM's spatial relationships and surface properties. An example of that semantic information is color, which has been utilized extensively in object recognition. For instance, a research effort [8] used color information to recognize different structural steel components using Hue, Saturation, and Intensity (HIS) instead of RGB Red, Green, Blue (RGB) to overcome illumination challenges. Other works investigated the use of

RGB values as features in a supervised learning algorithm to detect the rebar of reinforced precast concrete from a point cloud [9]. Another study [10] considered a colored point cloud to detect open, semi-open, and closed doors. Although the previous studies' results were satisfactory, the methods used were either able to detect one type of element or depend on the dataset and never rely on credible BIM sources.

Recent efforts in related fields have focused on Derivative-Free Optimization (DFO). DFO maximizes or minimizes the objective function in which the gradients are not helpful or cannot be computed [11]. Extensive research on DFO development resulted in many algorithms, such as CMA-ES [12], and DFO [13]. In civil engineering, CMA-ES was used to optimize a steel truss space and update the BIM model to match as-built states [14]. This was done by automatically manipulating the shape and pose parameters of BIM to fit 3D point clouds using genetic algorithms (GA) and simulated annealing (SA) [14]. Other studies contributed significantly to the exploration of CMA-ES in the AEC field whereby the reconstruction of BIM from 2D images [15] and a point cloud [16] was achieved by applying the CMA-ES algorithm.

Therefore, the primary aim of this paper is to advance the Derivative-Free Optimization-based approach to automatically detect 3D objects from point clouds using available BIM data and register the associated semantic information to each detected object by utilizing geometric and color features.

2. Methodology

The proposed framework comprises three modules, namely geometry scanner, geometry sampler, and CMAES optimizer (Fig.1).

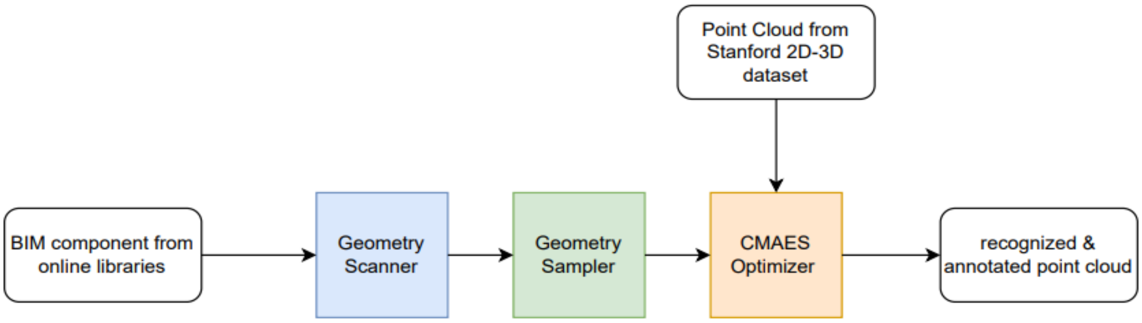

Fig. 1. Proposed framework and key modules.

2.1. First Module: Geometry Scanner

The geometry scanner starts by detecting the BIM components' geometry. From this geometry, instances are extractedwhich end up having solids with meshes. Meshes are then used to bring out triangles with vertices where color information representing the model materials is stored. Following the extraction of color information, a reconstruction process is implemented from vertices to the 3D model. Within this module, semantic information is extracted as well for each BIM element.

2.2. Second Module: Geometry Sampler

After geometry scanning, a sampler is constructed with determined density and applied to the model as a function. The proposed system's sampler mainly works by extracting all distinct points of each model from triangles and assigning point indices to related triangles. Once triangles and points are obtained, the proposed algorithm sets them in a polygon and correlates points with color in case color is selected. Following the previous steps, a sampled semantic BIM model is obtained using Point Cloud Library (PCL).

2.3. Third Module: CMAES Optimizer

The third module consists of an optimizer that takes the sampled BIM model and point cloud as inputs (Fig. 1), performs CMA-ES to minimize the objective function, and finally delivers a point cloud and its semantic information as a log txt file. To solve this problem, some mathematical algorithms like DFO can approximate the objective function without using its derivatives. Thus, the objective function can be defined as follows:

$$minimize \qquad f(X) \quad MSE(BIM(X), PC) = \frac{1}{n}\sum_{i=1}^{n}(X_{BIM} - X_{PC}) \qquad (1)$$

Where X_{BIM} = the points of BIM model surfaces; X_{PC} = the points of point cloud taken from the dataset; and $f(X)$ is the objective function.

More specifically, parameters of the objective function are the CMA-ES version, the density of sampled models, initial step size (sigma), number of offspring per generation (lambda), tolerance, and number of algorithm iterations (max-iteration). After defining the parameters, the scene is set and the optimizer is called on a specific model cloud to return the best-fit rotation and translation.

In order to study the robustness of various registration types, texture and color information is used to examine the geometry registration against a combined one (geometry and color).

3. EXPERIMENTAL SETUP AND RESULTS

In this study, an office scene point cloud was selected from the 2D-3D Stanford dataset that contains two tables and 23 chairs as shown in Fig.2a. A selection of 3D BIM models was obtained from online architectural model libraries (Fig.2b) based on their relevance to the dataset and suitability for analysis. Only two tables and ten chairs were tested during this study for comparison purposes. The CMAES parameters were appropriately selected (e.g. sigma=2 and lambda=32) and both scenarios were tested; (1) geometry and (2) geometry & color features.

Fig. 2. (a) An office scene from Stanford 2D-3D dataset; (b) BIM models from online libraries.

The experiments were processed by a workstation with AMD EPYC 7551-core processor (2 GHz, 32 cores, two logical processors), 64 GB memory, and Windows 10 Enterprise 64 bit operating system. Experimental results are shown in Table 1, Fig 3, and Fig 4.

Table 1. Comparison of different features used in the experimental scene (Table=2, Chair=10)

Evaluation	Scenario 1: geometry		Scenario 2 : geometry & color	
	Tables	Chairs	Tables	Chairs
Number of matched components	1/2	8/10	2/2	9/10
Number of iterations	3198		2353	
Precision (%)	50	88.8	100	90
Recall (%)	100	89	100	100
F1 Score (%)	66.6	89	100	94.6
Time (s)	72		123	

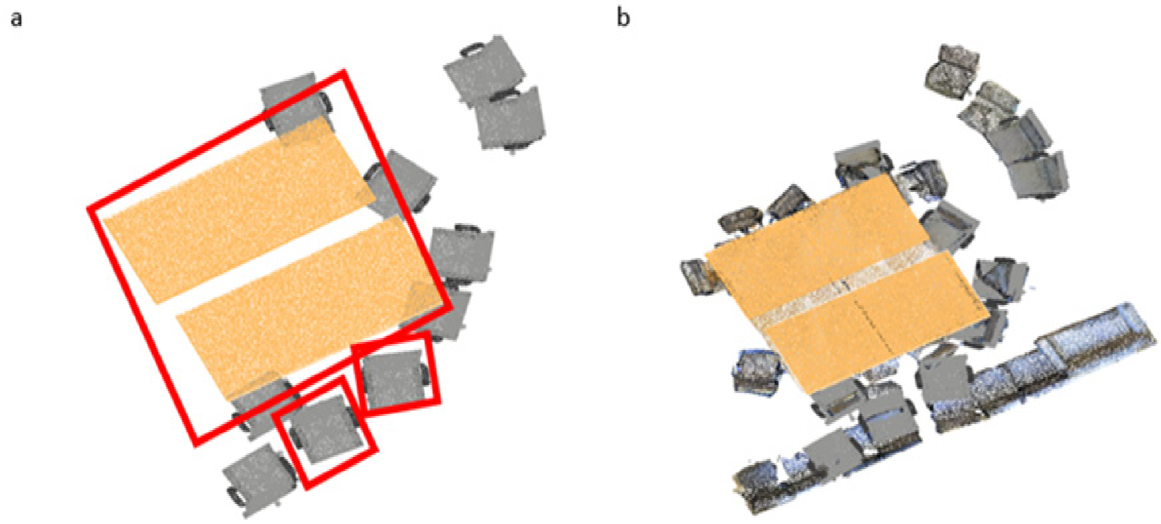

Fig. 3. Visual comparison of the registered point cloud using geometry features (a) generating a point cloud from BIM; (b) top view of a scene and generated point cloud.

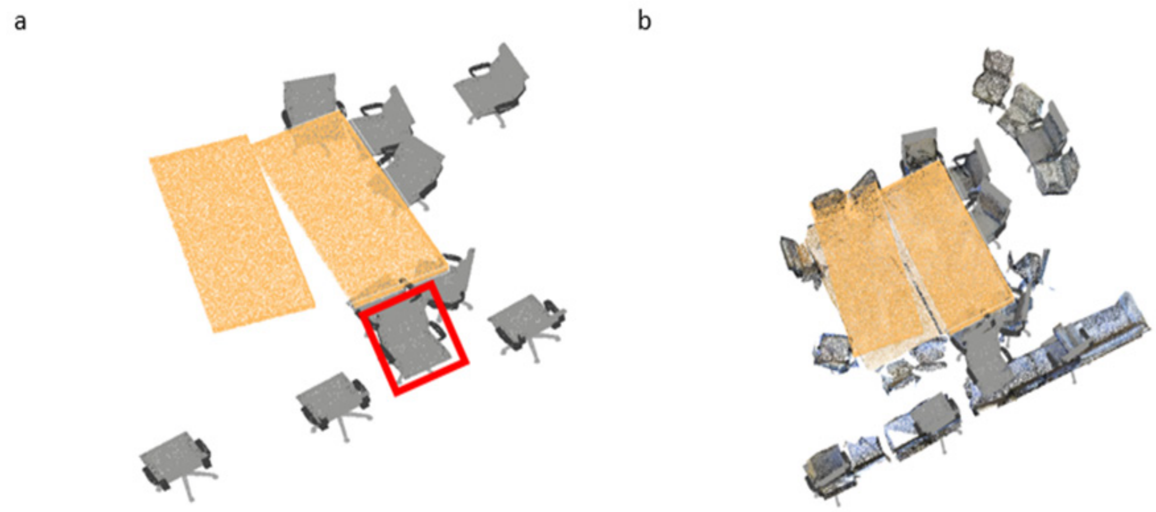

Fig. 4. Visual comparison of the registered point cloud using geometry & color features (a) generating a point cloud from BIM; (b) top view of a scene and generated point cloud.

Results revealed that the performance was improved by at least 5% when removing noise, shaded surfaces, and using color and space features. Furthermore, the results demonstrated that having color information in addition to geometry features reduces the number of iterations (Table 1). The performance of the proposed framework was further evaluated by calculating precision, recall, and F1 score, which are expressed by the following equations:

$$Precision = \frac{TP}{TP+FP} \quad (2)$$

$$Recall = \frac{TP}{TP+FN} \quad (3)$$

$$F1 = 2 * Precision * \frac{Recall}{Precision+Recall} \quad (4)$$

Where TP = True Positive (Positive in location and translation), FP = False Positive (detected component with error in translation or rotation), FN = False Negative (undetected component).

In this case, the precision, recall, and F1 score values (Table 1) reinforce the importance of using both geometry and color to enhance the framework performance.

4. Conclusion

In this paper, a novel approach comprising three modules was presented that uses available BIM data to automatically detect 3D objects from point clouds. Geometry and color features were used to register correlated semantic information to each detected object. The proposed framework registers information as a log text file to the generated point cloud based on the as-designed BIM models and point clouds while minimizing the Mean Squared Error (MSE) value. Experiments were conducted on an office point cloud taken from the Stanford 2D-3D dataset and preliminary results showed promising results, thereby suggesting that the proposed approach can significantly improve the accuracy and efficiency of as-built construction models.

While the proposed framework has shown promising results in detecting semantically enriching objects, there are several avenues for future work. One ongoing area of research is the integration of the framework within Revit as an addin to further automate the process. Further work aims at exploring the use of ORB-SLAM2 in conjunction with point clouds and BIM models to improve the framework's performance in complex construction environments.

Acknowledgments

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References

[1] Q. Wang, J. C. P. Cheng, and H. Sohn, "Automated Estimation of Reinforced Precast Concrete Rebar Positions Using Colored Laser Scan Data," *Computer-Aided Civil and Infrastructure Engineering*, vol. 32, no. 9, pp. 787–802, Sep. 2017, doi: 10.1111/mice.12293.

[2] R. Sacks, L. Ma, R. Yosef, A. Borrmann, S. Daum, and U. Kattel, "Semantic Enrichment for Building Information Modeling: Procedure for Compiling Inference Rules and Operators for Complex Geometry," *Journal of Computing in Civil Engineering*, vol. 31, no. 6, Nov. 2017, doi: 10.1061/(asce)cp.1943-5487.0000705.

[3] Y. Hu, Z. Chen, and W. Lin, "RGB-D SEMANTIC SEGMENTATION : A REVIEW School of Remote Sensing and Information Engineering , Wuhan University , Wuhan , China Department of Electronic Engineering , Shanghai Jiao Tong University , Shanghai , China," *2018 IEEE International Conference on Multimedia & Expo Workshops (ICMEW)*, pp. 1–6, 2018.

[4] A. Hermans, G. Floros, and B. Leibe, "Dense 3D semantic mapping of indoor scenes from RGB-D images," *Proc IEEE Int Conf Robot Autom*, pp. 2631–2638, 2014, doi: 10.1109/ICRA.2014.6907236.

[5] M. Rouhani, F. Lafarge, and P. Alliez, "Semantic segmentation of 3D textured meshes for urban scene analysis," *ISPRS Journal of Photogrammetry and Remote Sensing*, vol. 123, pp. 124–139, 2017, doi: 10.1016/j.isprsjprs.2016.12.001.

[6] J. W. Ma, T. Czerniawski, and F. Leite, "Semantic segmentation of point clouds of building interiors with deep learning: Augmenting training datasets with synthetic BIM-based point clouds," *Autom Constr*, vol. 113, no. March, p. 103144, 2020, doi: 10.1016/j.autcon.2020.103144.

[7] Y. Perez-Perez, ; Mani Golparvar-Fard, and K. El-Rayes, "Convolutional Neural Network Architecture for Semantic Labeling Structural and Mechanical Elements."

[8] H. Son and C. Kim, "3D structural component recognition and modeling method using color and 3D data for construction progress monitoring," *Autom Constr*, vol. 19, no. 7, pp. 844–854, 2010, doi: 10.1016/j.autcon.2010.03.003.

[9] Q. Wang, J. C. P. Cheng, and H. Sohn, "Automated Estimation of Reinforced Precast Concrete Rebar Positions Using Colored Laser Scan Data," *Computer-Aided Civil and Infrastructure Engineering*, vol. 32, no. 9, pp. 787–802, 2017, doi: 10.1111/mice.12293.

[10] B. Quintana, S. A. Prieto, A. Adán, and F. Bosché, "Door detection in 3D coloured point clouds of indoor environments," *Autom Constr*, vol. 85, pp. 146–166, 2018, doi: https://doi.org/10.1016/j.autcon.2017.10.016.

[11] H.-M. Gutmann, "A radial basis function method for global optimization," *Journal of global optimization*, vol. 19, no. 3, pp. 201–227, 2001.

[12] N. Hansen, "The CMA Evolution Strategy : A Tutorial.he CMA Evolution Strategy : A Tutorial," 2011.

[13] K. Scheinberg, "Manual for Fortran software package DFO v2. 0." 0. Technical report, 2003.

[14] A. Kaveh, M. Kalateh-Ahani, and M. S. Masoudi, "The CMA evolution strategy based size optimization of truss structures," *دانشگاه علم و صنعت ایران*, vol. 1, no. 2, pp. 233–256, 2011.

[15] F. Xue, W. Lu, and K. Chen, "Automatic Generation of Semantically Rich As-Built Building Information Models Using 2D Images: A Derivative-Free Optimization Approach," *Computer-Aided Civil and Infrastructure Engineering*, vol. 33, no. 11, pp. 926–942, Nov. 2018, doi: 10.1111/MICE.12378.

[16] F. Xue, W. Lu, K. Chen, and A. Zetkulic, "From Semantic Segmentation to Semantic Registration: Derivative-Free Optimization-Based Approach for Automatic Generation of Semantically Rich As-Built Building Information Models from 3D Point Clouds," *Journal of Computing in Civil Engineering*, vol. 33, no. 4, pp. 1–16, 2019, doi: 10.1061/(ASCE)CP.1943-5487.0000839.

AUTOMATED CLASSIFICATION AND CODING FOR BIM COMPONENTS BASED ON APPLICABLE BIG DATA

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Abstract

For the application of BIM technology, BIM models play a vital role in transferring and sharing building information. BIM models represent the building information through the attributes of components, such as walls and slabs, and the relationship between these components. Among all the attributes of components in BIM models, the classification and coding attribute is essential to retrieve the building information in a quick way. However, in practice, the BIM models that are prepared by using a BIM authoring tool cannot ensure complete and correct classification and coding attribute when they are transferred into the format of another tool. Besides, BIM models prepared by using 3D reconstruction technology also lack the classification and coding attribute. Missing or incorrect classification and coding attribute of BIM components impedes the fully exploitation of BIM model greatly. To solve the problem, this paper proposes an automated classification and coding method for BIM components based on a batch of BIM models with components labeled with key features and type, which can be obtained from the big data of the BIM models that have been correctly used. In the method, the association rule mining algorithm is used to establish the classification and coding rules for BIM components based on the labeled component data set. Then, for any BIM component, an algorithm based on the credibility reasoning approach is used to execute the rules and obtain its classification and coding attribute. In this way, the classification and coding attribute can be determined for any BIM component according to any given standard. The method is validated by developing a prototype based on Autodesk Revit and by using a batch of BIM models from structural design, and 92.7% precision is achieved in the test case. This method contributes to the quick classification of BIM components.

Keywords: Building information modeling, association rule mining algorithm, classification and coding.

1. Introduction

BIM (Building Information Modeling) is an essential carrier of information for the entire lifecycle of a construction project. The BIM model database is the core resource for BIM applications in construction projects [1]. Standardized classification and coding of the components in BIM models are prerequisites for accurately retrieving and accessing components in BIM models. This is also a necessary condition for BIM technology to be used for supporting the sharing of building information data throughout the entire lifecycle of a construction project [2]. For example, because various construction robots have different construction targets, a wall polishing robot only needs wall data from the building information model. Therefore, both the accurate retrieval and access of wall model components from the structural BIM model, and the transmitting of the wall data to the wall polishing robot are prerequisites for the smooth implementation of subsequent work.

To standardize the classification and coding of BIM components and facilitate the exchange and sharing of information throughout the entire lifecycle of a construction project, some countries have established building classification and coding standards, such as Uniformat II, Omni Class and so on. To promote the rapid development of China's construction industry, a series of building product classification and coding standards have also been established, including “Standard for classification and coding of building information model (GB/T 51269-2017)” and “Classifying and coding of construction products (JG/T 151-2015)”. Among them, the former is a standard related to the IFD (International Framework for Dictionaries) and was established by referring to OmniClass. It is applicable to the classification and coding of BIM models in civil buildings and general industrial buildings. This standard, which is intended for the construction engineering field, stipulates the standard for classification and coding for various types of information. The coding structure includes table codes, major category codes, intermediate category codes, minor category codes, and detailed category codes, with each level of code represented by two Arabic numerals. For example [3], the code 14-10.20.36.06 represents the code for outdoor stairs, with the table code being 14, the major category code being 10, the intermediate category code being 20, the minor category code being 36, and the detailed category code being 06.

As a carrier of building information, BIM models are transferred and utilized among different modelling application software, including building energy simulation software and cost estimation software, which requires accurate classification of components in a BIM model. Failure to properly classify the BIM components during the modelling process, loss of information during storage and transmission, or inability to recognize during component information extraction can result in missing classification information for BIM components, which in turn impede the subsequent model information processing work [4]. In addition, with the help of BIM software, it is relatively easy to perform component classification and add semantic information during the modelling process [5]. Nevertheless, a 3D model created from point cloud data contains only geometric information and lacks semantic information [6]. Therefore, the problem of missing or incorrect classification and coding attribute of components in the obtained BIM models is widespread and significant, which severely impedes the further application of BIM technology in various tasks and stages, such as design, construction and operation. Moreover, due to the complexity of the classification and coding standards for components in a BIM model, the variety and large number of designed components, the cost of manual classification and coding is high and prone to errors. In response to these problems, it is obvious that automatic classification and coding tools are needed.

Consequently, this study aims to establish an automatic classification and coding method for structural components in BIM models, and develop a plugin based on an authoring tool of BIM model, taking

Autodesk Revit as an example, for customization to add classification and coding attributes to components in structural BIM models automatically, in which the classification and coding attribute of these components are obtained through rule reasoning. The rules used for the reasoning are obtained from a labelled data set through data mining algorithms. Through the method proposed in this study, the classification and coding attributes of structural components in BIM models can be replenished automatically, which contributes to promote the deepening application of BIM.

2. Related works

There are mainly two types of researches related to automatic classification and coding methods for components in a BIM model, i.e., those based on machine learning and those based on rule-based reasoning.

In the methods based on the machine learning, the overall process can be summarized as follows [7,8]. Firstly, a portion of components in a BIM model in the data set are selected, and their semantic information, such as name, code, type, size, and fill ratio, is manually labelled as the training set for the machine learning algorithm. After that, based on the selected data set, the machine learning model is trained with the labelled data set to predict the coding information of unlabelled objects, by using methods such as decision trees, neural networks, and support vector machines. After training, the model needs to be tested to see if it can perform well on the test set. Ultimately, once the model is evaluated and deemed satisfactory, it can be used to fill in the semantic information of unlabelled components automatically and thus add the classification and coding attribute for components in a BIM model automatically [9]. According to the above process, Bloch et al. [10] trained an automatic room classification model using a multiclass neural network algorithm on the AZURE ML platform, with 150 BIM model instances as samples, 70% of which is used as the training set, and 30% is used as the testing set. A multiclass neural network algorithm is used for spatial classification of residential apartments. The results indicated that the machine learning-based method was useful and efficient for room classification. Koo et al. analysed the geometric dimensions and spatial relationships of these components, based on a data set of 4187 independent components in a BIM model from six architectural BIM models. Next, identified unconventional or outlier data that may require further analysis to improve the reliability of the component classification model, through using support vector machine and introducing a novelty detection algorithm. The evaluation results indicated the effectiveness of the algorithm for automatic classification and coding of components in a BIM model [11]. As described above, the structural components in a BIM model can be classified and encoded through machine learning methods. Objects such as tables, chairs, safety cones, etc. in construction sites, office spaces, and other settings can also be identified and classified using machine learning methods. Ferguson et al. designed an algorithm that can be used for both 2D image data and 3D point cloud data to recognize objects such as trash cans and safety cones at construction sites. The study collected 1214 RGB-D image data as the training data set and 255 RGB-D image data as the testing data set to conduct object classification experiments, which was verified to be available for classification and coding of components [12]. As mentioned above, different algorithms are required to classify and code components in a BIM model in different scenarios based on machine learning method. Meanwhile, it is necessary to manually establish large-scale data set and label them, which is highly dependent of manual operations.

The rule-based inference methods are widely used for the classification and coding of components in a BIM model. Firstly, formulating rules are found and selected, through the analysis of the relevant knowledge of components in a BIM model. Each component in the BIM model would be classified, after being identified according to the rules. For the components that cannot be identified based on rules, their information can be manually marked to supply the rules; finally, the classification and coding results would be validated and corrected to ensure their accuracy and consistency [13] For example, the name of components in BIM models would be checked to ensure accuracy, the size and material would be checked to match the design document, etc. Some researchers established rule sets to infer the classification and coding of BIM models by acquiring the knowledge of domain expert, and adding inferred classification and coding attribute to the components [14]. To classify components in a BIM model through a customized matching algorithm, and to provide mathematical measures of matching results at the same time [15]. The rule-based method has also been applied to establish rule sets for inferring the classification and coding of components in a BIM model based on their geometric attributes and geometric theorems. This method involves algorithm construction, extraction of objects of components in BIM models, object classification, semantic filling, classification result verification, and algorithm evaluation [16]. As illustrated above, the rule-based reasoning method relies on the knowledge of domain experts, and its effectiveness is also influenced by the methods and accuracy of rule content transformation.

To address the limitations of previous studies, this research proposes the data mining approach to classify and code structural components in BIM models as an example. The method aims to mine the classification and coding rules from a large data set of components of BIM models, avoiding the high requirement for domain experts' knowledge and the impact of rule transformation and accuracy on the effectiveness of the method. Firstly, a data set for rule mining is formed by collecting and processing structural BIM models. Then, to apply the association rule mining algorithm to obtain rules for classification and coding automatically. Finally, to introduce the credibility reasoning approach to fully consider the uncertainty of rules, and thus achieve the automatic classification and coding of these components. This method is also expected to be applicable to the automatic classification and coding of other types of components such as MEP components. To achieve the objective the credibility reasoning approach is introduced in this phase.

3. Methodology

The classification and coding method for structural components in BIM models proposed in this paper consists of three phases: data preparation, rule mining, and credibility reasoning. As shown in Fig. 1, this section will provide a detailed explanation of each phase.

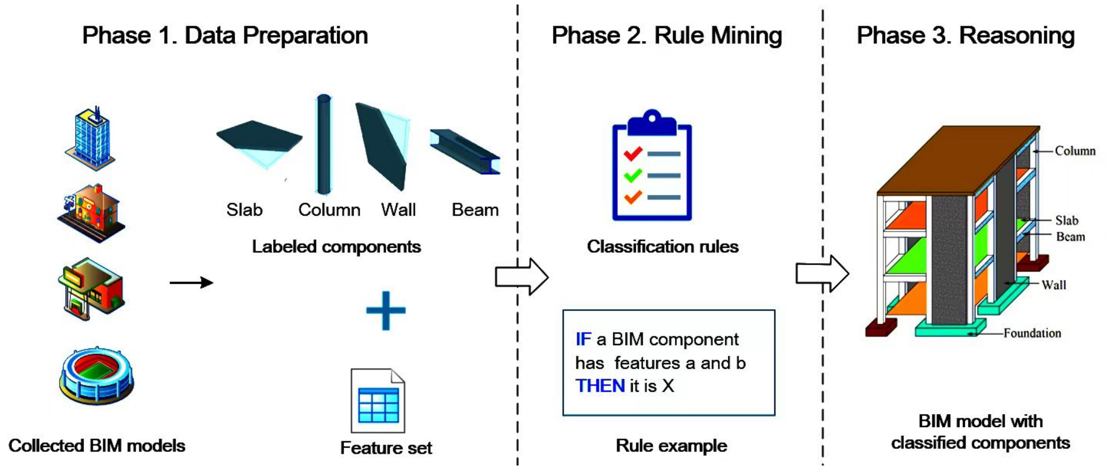


Fig. 1. Process overview of method

(1) Data preparation. The main objective of the phase is to provide the data of structural components in BIM models for rule mining, which includes BIM models collection, and components labelling with beams, slabs, columns, walls, and component features design. Then, the feature design of the component is aimed at obtaining the values of various features of the component, thereby forming a data set for rule mining. The feature design and data set establishment of the component is the prerequisites for rule mining.

(2) Rule mining. The main purpose of this phase is to apply association rule algorithm for rule mining, and to establish a rule set for automatic classification and coding of components in BIM models, including three steps: obtaining frequent item sets from the data set, generating rules from frequent item sets, and controlling the size and quality of the rule sets. The quality and quantity control of the rule sets is the foundation for ensuring the accuracy of classification and coding.

(3) Reasoning. The main objective of this phase is to reduce or eliminate the uncertainty inherent in the rules established by using data-driven methods, including two steps: calculating the internal certainty factor of the rules and calculating the certainty factor of the classification and coding results when a given component feature matches the rules.

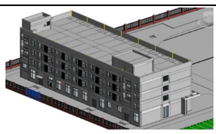
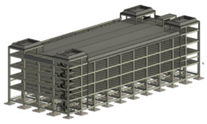
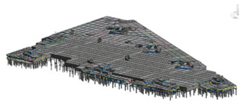
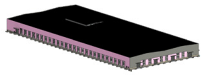
4. Data preparation

The proposed the data mining approach consists of three phases, namely feature design, data set establishment, and rule mining. Considering the requirement on the consistency in the classification and coding standards, this research will be carried out with reference to the “Standard for classification and coding of building information model (GB/T 51269 – 2017)”. The method is expected to be also applicable to other standards.

4.1 Data collection

The data for structural components in BIM models used in this study mainly includes the structural BIM models of four actual building projects. Through the analysis of 8838 components in the BIM models of these projects, a data set for rule mining was established. The quantity of various types of components for each project is presented in Table 1.

Table 1. Overview of collected BIM models

NO.	Model 1	Model 2	Model 3	Model 4
Image				
No. of beam	311	422	1221	396
No. of column	156	342	1838	375
No. of slab	265	89	1738	22
No. of wall	670	0	896	97

4.2 Feature extraction

The values of various features of structural components in BIM models were obtained, through the development of plugins using the Revit API, thus forming a data set for rule mining. The format of this data set used for rule mining is stored in a standard text file format, which follows the convention of “component category (label) + feature name: feature value”. The features of the components can be mainly divided into two categories: attribute features and relationship features. Attribute features include surface area and volume, while relationship features include component intersection and parallelism. Among them, the attribute feature is usually divided into geometric features and non-geometric features, for example, “aspect ratio” is a geometric feature, and “fill rate” is a non-geometric feature. The value types of features are divided into continuous types and discrete types. For example, the “volume of these components” feature has a continuous value type, while the “whether the component intersects with a column” feature has a discrete value type.

The process of features designing of structural components in BIM models must ensure the effectiveness of the selected component features and their values. For example, the feature “structure material is concrete” is not an effective feature for distinguishing between beams and columns. The feature “longest vertical edge” is an effective feature for distinguishing between columns or walls but not plates. After conducting testing on the geometric dimensions, volume, surface area, material, and other attributes of components in BIM models, it was found that the effectiveness of material, location, and other attribute features in component classification and coding is insufficient and they are not included in the feature set for the classification and coding of components in BIM models in this study. After an extensive literature review and repeated experimental testing, a set of features for the classification and coding of components in BIM models was identified. The geometric features of the properties include aspect ratio, short-to-medium ratio, fill rate, whether it is a hexahedron, surface area, volume, and vertical extension. The relational attributes include whether it intersects with walls, columns, beams, foundations, and floor slabs. The types, names, and meanings of features of these components in a BIM model are presented in Table 2 for reference.

Table 2. Feature definitions

Feature type	Feature name	Explanation
Geometric feature	Short-long ratio	The ratio of the shortest edge to the longest edge of the bounding box of the component.
	Short-middle ratio	The ratio of the shortest edge to the second-longest edge of the bounding box of the component.
	Fill ratio	The fill ratio of the volume of the component to the volume of the bounding box of it.
	Face number	The face number of the component.
	Surface area	Surface area of the component.
	Volume	Volume of the component.
	Vertically extended	Whether the member extends vertically.
Relational feature	Relation with wall	Whether the component intersects a wall.
	Relation with column	Whether the member intersects a column.
	Relation with beam	Whether the member intersects a beam.
	Relation with foundation	Whether the member intersects a foundation.
	Relation with slab	Whether the member intersects a slab.

5. Rule mining

Due to the low requirement for domain knowledge for data-driven rule mining methods, the methods are capable of continuously optimizing rules from expanded data. Additionally, rule mining is supported by mature algorithms with strong generality. In this paper, the data mining approach was applied to establish rules for the classification and coding of structural components in BIM models. Based on the obtained data set, the association rule mining algorithm was applied to obtain rules for classification and coding automatically. As a widely used data mining algorithm, the association rule mining algorithm discovers frequent combinations of feature values that co-occur with specific component types in the data set, i.e., frequent item sets, forming "IF-THEN" decision rules. The "IF" part is the antecedent, which expresses a set of feature values of component, while the "THEN" part is the consequent, which expresses the classification and coding result for the component.

The process of rule mining using the association rule mining algorithm can be divided into three steps. Namely, firstly, to extract frequent item sets from the data set, which are statistical patterns of co-occurrence of feature values and component categories with high frequency. Then, to generate rules from frequent item sets, where the condition part of the rules consists of the feature values in the frequent item sets and the result part of the rules corresponds to the component types in the frequent item sets. Finally, to filter the rules to control the size and quality of the rule base and improve the efficiency and effectiveness of subsequent automatic reasoning processes. The selection criteria are divided into two categories: absolute standards and relative standards. Among them, the absolute criteria for rule selection include support and confidence, where support is the probability of frequent item sets appearing in the data set, which ensures the universality of the rule, while confidence is the conditional probability that the result holds when the condition occurs in the data set, ensuring the quality of the rule. Relative standards for rule selection involve comparisons within the rules themselves. For example, when comparing Rule A and Rule B with the same result, if the constraint conditions decrease while the confidence of the result increases, it indicates that compared to Rule A, Rule B introduces an additional constraint, which lowers the probability of the result being true. In that case, Rule A is better than Rule B, and Rule B should be eliminated from the rule sets to avoid conflicts within the rules. Here is an example,

(1) Rule A: If the longest edge is vertical (FALSE), the ratio of short to medium edges is greater than 0.4 and not less than 0.6 (TRUE), the connected base number is 0 (TRUE), then the component is judged to be a reinforced concrete beam with a confidence level of 0.994.

(2) Rule B: If the longest edge is vertical (FALSE), the ratio of short to medium edges is greater than 0.4 and not less than 0.6 (TRUE), the connected base number is 0 (TRUE), the surface area is less than 10 square meters (TRUE), then the component is judged to be a reinforced concrete beam with a confidence level of 0.954.

Compared with Rule B, Rule A has fewer constraints but a higher confidence level for the same result. Therefore, Rule A is better than Rule B. In Rule B, an additional constraint on the surface area is introduced, which lowers the confidence level of the rule, and therefore, Rule B will not be included in the rule sets for the reinforced concrete beam.

According to the test results, the threshold for support is set as 0.05 and that confidence as 0.8. Frequent item sets are obtained from the data set, and then rules are generated from the frequent item sets, and the rules are filtered finally. Among them, the filtering requirements are as follows: support > 5%, confidence > 80%, and there is no better rule. A total of 114 rules for columns, walls, beams, slabs, and other structural components in BIM models are established. Taking the rules for reinforced concrete beams as an example, the classification and coding rules for beams obtained by using this algorithm are shown in Table 3.

Table 3. Classification and coding rules for reinforced concrete beams established using the data mining approach

No.	Rule
1	IF the vertical edge is the longest (FALSE) AND the ratio of short to medium sides is greater than 0.4 and not less than 0.6 (TRUE) AND the connected bases number is 0; THEN it is a reinforced concrete beam.
2	IF the vertical edge is the longest (FALSE) AND the ratio of short to medium edges is greater than 0.4 and not less than 0.6 (TRUE); THEN the component is a concrete beam.
3	IF the vertical edge is the longest (FALSE) AND surface area is less than 10 square meters (TRUE) AND number of connected columns is 0 (TRUE) AND the connected base number is 0 (TRUE); THEN it is a reinforced concrete beam.
4	IF the vertical edge is the longest (FALSE) AND surface area is less than 10 square meters (TRUE) AND number of connected bases is 0 (TRUE); THEN it is a reinforced concrete beam.
5	IF the vertical edge is the longest (FALSE) AND surface area is less than 10 square meters (TRUE) AND number of connected columns is 0 (TRUE); THEN it is a reinforced concrete beam.
6	IF the vertical edge is the longest (FALSE) AND surface area is less than 10 square meters (TRUE); THEN it is a reinforced concrete beam.

7	IF the ratio of short side to medium side is greater than 0.4 and not less than 0.6 (TRUE) AND number of connected bases is 0 (TRUE); THEN it is a reinforced concrete beam.

6. Reasoning

According the pre-established rule base, a component of unknown type is classified by matching its features with the condition clauses of these rules. Considering the uncertainty of rules established by using data-driven methods, this study introduces the credibility reasoning approach to ensure the completeness, consistency, and rationality of the classification process.

In the theory of the credibility reasoning approach, the uncertainty of rules in the form of "IF E, THEN H" is evaluated by the parameters of certainty factor (CF), including the three types, i.e., CF(H, E), CF(E) and CF(H). CF(H, E) is used to evaluate the uncertainty of the logical relationship between the conditions (E) and result (H). Besides, the uncertainty of the conditions in a rule also needs to be considered. For example, in most cases, the qualitative conditions have higher uncertainty than quantitative conditions. To handle the uncertainty, CF(E) is a parameter to evaluate the matching degree between the given component feature values and the conditions with uncertainty. Apparently, for a condition without uncertainty, the value of CF(E) is TRUE (1) or FALSE (0), in which 0 means not matching, and 1 means matching. CF(H) indicates the reliability when a result is deduced. Table 4 gives the definitions and explanations of these parameters.

In the classification and coding method based on the credibility reasoning, CF(H) is the decisive indicator to draw the result. Namely, after matching the features of a structural component with all the rules, the final type of the component is the result of the matched rule with the highest CF(H). Thus, the calculation processes of CF(H) are introduced. Firstly, the base case is considered when only one rule is matched. On this basis, the calculation process when multiple rules are matched is given [17].

Table 4. Definitions and explanations of parameters

Parameter	Definitions	Explanations
E	The conditional part of the classification and coding rules.	Production rule: IF E, THEN H.
H	The result part of the classification and coding rules.	Production rule: IF E, THEN H.
CF(E)	The certainty factor of condition E.	The degree of matching between the given component feature values and the conditions E in the rules. The value is either 0 or 1, where 0 means rule matching failure, and 1 means rule matching success.
CF(H, E)	The certainty factor of the classification and coding rule "IF E, THEN H".	To reflect the strength of the relationship between the premise condition E and the result H.
CF(H)	The certainty factor that the result H holds under the condition of matching the component characteristics with the rule.	The final rule-based inference result is the one with the highest degree of certainty factor.
P(H)	The probability of result H being true.	To be calculated by statistical analysis of 8,838 components in the data set.
P(H|E)	The conditional probability of the result of H being true when the condition E is true, namely, the confidence.	To be calculated from the results of rule mining.

If only one rule is matched, according to theory of the credibility reasoning approach, the CF(H) depends on the value of CF(H, E) and CF(E), as shown in Equation (1).

$$\mathrm{CF(H)=CF(H,E)} * \mathrm{CF(\ E)} \quad (1)$$

Because the conditions of the classification and coding rules are quantitative and has no uncertainty, the value of CF(E) is TRUE (1) or FALSE (0) and can be obtained directly from the matching result. Thus, the value of CF(H) can be obtained by calculating the value of CF(H, E) by using Equation (2).

$$\mathrm{CF(H,E)} = \begin{cases} \frac{\mathrm{P(H|\ E)\text{-}P(H)}}{\mathrm{1\text{-}P(H)}}, & \mathit{if}\ \mathrm{P(H)} \neq 1 \\ 1, & \mathit{if}\ \mathrm{P(H)=1} \end{cases} \quad (2)$$

Where P(H|E) is the probability of result H when the condition E is matched and it is equal to the confidence of a rule in the rule mining process according to the definition. P(H) is the probability for “the result is true”. Specific to the classification and coding rules, the result of a certain component type and the P(H) can be obtained by counting the frequency of component types in the data set.

Based on the calculation equation of CF(H) in the case that only one rule is matched, when n (n>1) rules with the conclusion H are matched, the CF(H) can be calculated by using an iterative process, as shown in Fig. 2. As the known conditions of the process, n rules with the conclusion H are matched and the certainty factors of the i-th (1⩽i⩽n-1) rule of the n rules, i.e., CF_i (H), can be obtained by the Equation (1). In the first step of the process, CF(H) is initialized by CF_1 (H). Then, in each iteration of the process, the other rules are handled one by one and the value of CF(H) is updated by using Equation (3).

$$\mathrm{CF(H)=CF(H)+CF_i(H)\text{-}CF(H)} * \mathrm{CF_i(H)} \quad (3)$$

Thus, after n-1 iterations, the final CF(H) is calculated and the iterative process ends [15]. Note that in the process, the calculation result of CF(H) is independent of the sequence of the matched rules due to the commutative laws of Equation (3).

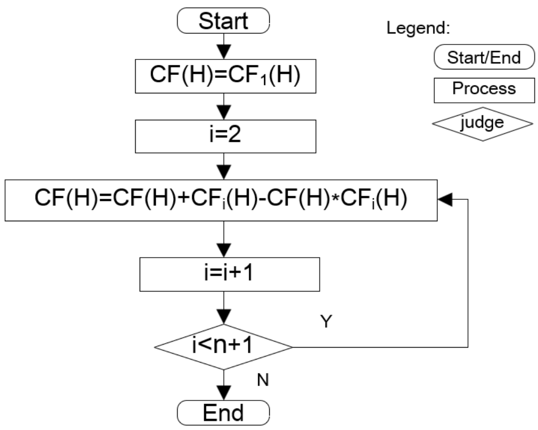


Fig. 2. Calculation process of CF(H) when multiple rules are matched

To clarify the process, an example is given when a component with unknown type matches all the following three classification and coding rules are matched when reasoning. The value of P(H) is 0.307, which was calculated by statistical analysis of 8,838 components in the data set.

(1) Rule 1: IF the vertical edge is the longest, and the volume is less than 2 cubic meters, and the number of connecting columns is 0, and the aspect ratio is greater than 0.1 and not less than 0.2, THEN the confidence level that the component is a concrete column. The value of P(H|E) of Rule 1 is 0.868. which was calculated from the results of rule mining. The value of $CF(H, E)$ of Rule 1 is 0.868, which was calculated by using Equation (2). The value of CF1 (H) of Rule 1 is 0.810, which was calculated by using Equation (1).

(2) Rule 2: IF the surface area is less than 10 square meters, the vertical edge is the longest, and the short-to-long ratio is greater than or equal to 0.1 but not less than 0.2, THEN the component is a concrete column. The value of CF2 (H) of Rule 2 is 0.808 by the same approach.

(3) Rule 3: IF the vertical edge is the longest, and the volume is less than 2 cubic meters, and the short-to-long ratio is greater than or equal to 0.1 and not less than 0.2, THEN the component is considered as a concrete column. The value of CF3 (H) of Rule 3 is 0.795 by the same approach.

After 2 iterations, the calculation result of the final CF (H) is 0.993, which was calculated according to Equation (3).

As demonstrated above, the rationality of certainty factor calculation and reasoning can be proven through rigorous mathematical derivation. The result of certainty factor depends on both rules themselves and the matching result. Among which, certainty factor of each rule can be obtained through rule-mining, then, the final certainty factor of one result corresponding to many rules can be calculated by using above equation. The introduction of the credibility reasoning approach ensures the completeness, consistency, and rationality of the reasoning process.

7. Case study and validation

To verify the effectiveness of the proposed method in this study, a customized plugin on the Autodesk Revit was developed. Then, a typical structural BIM model of an engineering project was selected to verify the effectiveness. The architecture of the customized plugin is shown in Fig. 3, which consists of three layers: the data layer, application layer, and interface layer.

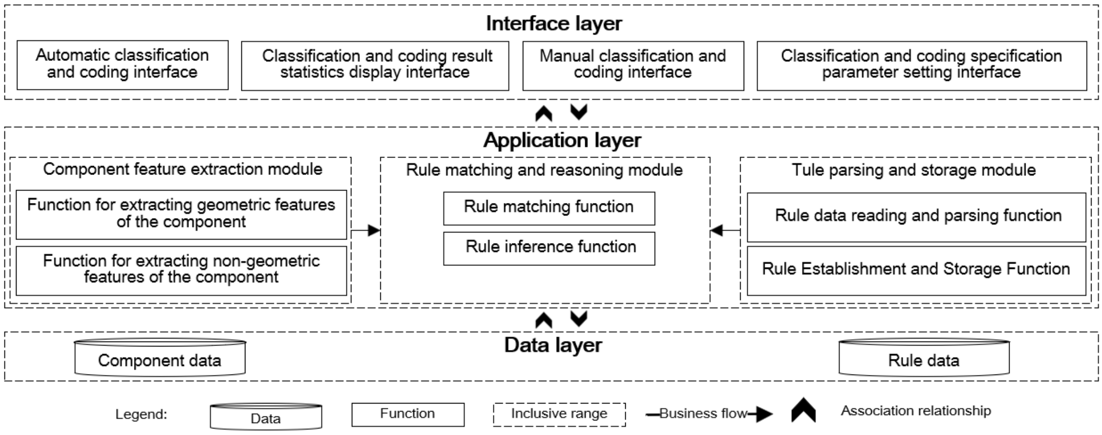


Fig. 3. System architecture for automatic classification and coding of structural components in BIM models

(1) The data layer consists of component data and rule data. The rule data is established and stored in text form, while the component attribute data in the Revit model is obtained through the customization of Autodesk Revit.

(2) The application layer consists of three modules that implement the functionality of BIM model structural component classification and coding, including the component feature extraction module, rule parsing and storage module, and rule matching and reasoning module. The rule parsing and storage module is used to parse the rule data in the data layer, read the rule text file, and convert it into a format that can be understood by the computer. The rule matching and reasoning module processes the parsed rule data and component data, performs reasoning, and inputs the classification and coding results of the components to be classified.

(3) The interface layer provides operational entry points for software users, including the automatic classification and coding interface, the classification and coding result statistics display interface, the manual classification and coding interface, and the classification and coding specification parameter setting interface.

Importing BIM models with incomplete classification and coding attribute into the software allows for automatic identification of unclassified components and addition of coding information. Additionally, the software can export reports on the classification and coding of structural components in BIM models. The user can execute the procedure by following the subsequent steps. First, set classification and coding parameters, including selected standards, the profession of the model to be classified, and the location of the exported report. Second, upon launching the automatic classification and coding program, the system will load the backend rule sets and execute reasoning to add attribute to these components automatically in the current view. Any components that were not able to be automatically classified will be isolated and displayed in the current view, as shown in Fig. 4. Third, the user can view the classification and coding results through the statistics entry. Double-clicking on any component will navigate the system to the location of the component for the user to view automatically. The user can also add attribute manually to the component through the manual classification and coding entry.

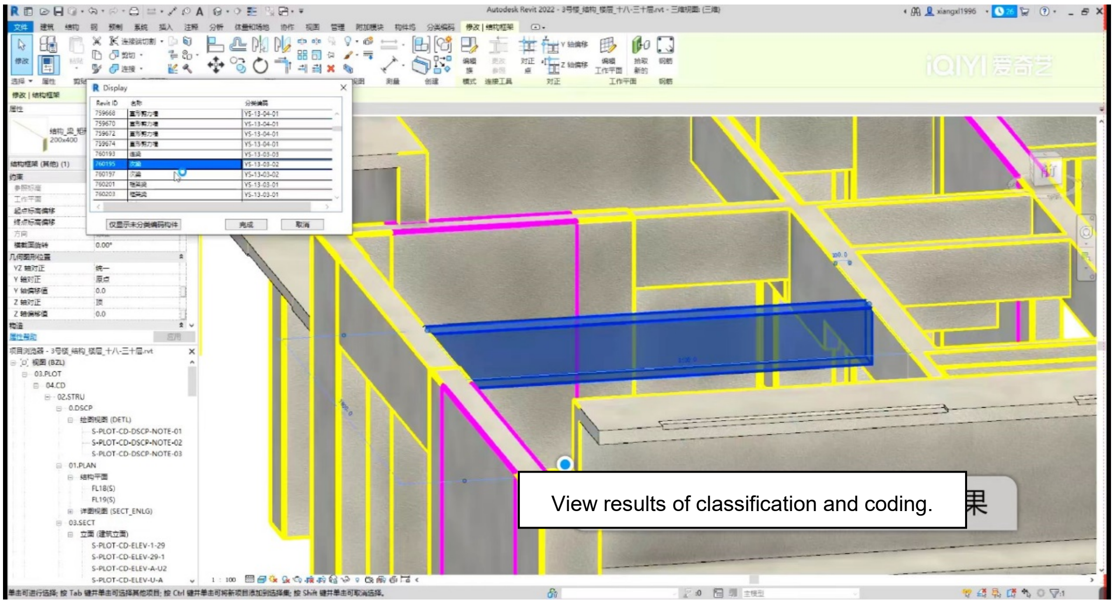


Fig. 4. Example of automatic classification and coding of structural components in BIM models

This study involved importing the structural BIM model of a particular real project into the verification process, which includes 454 components. Among these, 421 components were classified and coded successfully, with 92.7% precision was achieved. These components identified include YS-13-04-01 rectangular shear walls, YS-13-03-03 beams, YS-13-01-04 eaves, and others. The exported component classification and coding report can display the entire list of component codes and other information.

8. Discussion and Conclusion

This paper established a method to classify and code structural components of BIM models automatically considering the uncertainty of rules established by using data-driven methods. Furthermore, a customized plugin was developed for validation by using a batch of BIM models from structural design, and 92.7% precision is achieved in the test case. This method helps alleviate the problem of high dependence on domain expert knowledge in rule-based methods, and improves the efficiency and accuracy for replenishing the component attribute. By enabling fast and accurate component classification and coding, the use of BIM technology can be promoted in various stages and tasks such as design, construction, and maintenance. Nevertheless, there is still a risk of overfitting the training model in rule mining, due to the high quality and quantity requirements for the labelling of the structural BIM model training data set. Our future research will further expand on the data mining approach, with focusing on reducing the requirements for labelled training data or exploring the possibility of not labelled training data at all.

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References

[1] David Bryde, Marti Broquetas, Jtirgen Marc Volm, "The project benefits of building information modelling," International Journal of Project Management, pp. 971-980, 2013, doi.org/10.1016/jijproman.2012.12. 001.
[2] Rebekka Volka, Thu Huong Luu, Johannes Sebastian Mueller-Roemer, Neyir Sevilmis, Frank Schultmanna, "Deconstruction project planning of existing buildings based on automated acquisition and reconstruction of building information," Automation in Construction, pp. 226-245, 2018, doi:10.1016 j.autcon.2018. 03.017.
[3] GB/T 51269: "Standard for classification and coding of building information model," China Architecture and Architecture Press, 2017.
[4] Zhai Yiyang, Zhang Chi, Wang Bo, Wang Xue, Liu Kai, Tang Zhongze, "The standardization method and application of the BIM model for interchanges," Applied Sciences, pp. 87-89 2022, doi: 10.3390/ap p12178787.
[5] Xuehan Xiong, Antonio Adan, Burcu Akinci, Daniel Huber," Automatic creation of semantically rich 3D building models from laser scanner data," Automation in Construction, pp. 325-337, 2013, doi: 10.1016/ j. autcon2012. 10.006.
[6] Pingbo Tang, Burcu Akinci, "Formalization of workflows for extracting bridge surveying goals from laser-scanned data," Automation in Construction, pp. 306–319, 2012, doi: 10.1016/i.autcon.2012.09.006.
[7] Steven L. Brunton, J. Nathan Kutz, "Data-Driven Science and EngineeringMachine Learning, Dynamical Systems," andControl, Cambridge University Press, 2022, ISBN: 978-1-009-11563-6.
[8] Wei Shuangfeng, Liu Minglei, Zhao Jianghong, Huang Shuai, "A survey of methods for detecting indoor navigation elements from point clouds," Geomatics and Information Science of Wuhan University, pp. 2003-2011, 2018 doi: 10.13203/j.whugis20180144.
[9] F. Bosche, C.T. Haas, "Automated retrieval of 3D cad model objects in construction range images," Automation in Construction, pp. 499-512,2008, doi: 10.1016/j.autcon.2007.09.001.
[10] Tanya Bloch, Rafael Sacks, "Comparing machine learning and rule-based inferencing for semantic enrichment of BIM models," Automation in Construction, pp. 256-272, 2018, doi: 10.1016/j.autcon.2018.03.018.
[11] Koo, B., Shin, B., "Applying novelty detection to identify model element to IFC class misclassifications on architectural and infrastructure building information models," Journal of Computational Design and Engineering, pp. 391-400, 2018, doi: 10.1016/j.jcde.2018. 03.002.
[12] Max Ferguson, Seongwoon Jeong, Kincho H. Law, "Worksite object characterization for automatically updating building information models," Computing in Civil Engineering, pp. 303-311, 2019, doi: 10.1061/97807844824 21.039.
[13] Tarcisio Mendes de Farias, Ana Roxin, Christophe Nicolle, "A rule-based system for semantical enrichment of building information exchange," HAL Open Science, 2014, doi: 10.1016/j.eswa.2015.02. 029.
[14] Michael Belsky, Rafael Sacks, "Semantic enrichment for building information modeling," Computer-Aided Civil and Infrastructure, pp. 261-274, 2016, doi: 10.1111/mice.12128.
[15] Rafael Sacks, Ling Ma, Raz Yosef, Andre Borrmann, Simon Daum, Uri Kattel, "Semantic enrichment for building information modeling: Procedure for compiling inference rules and operators for complex geometry," Journal of Computing in Civil Engineering, 2018, doi: 10.1061/(asce) cp.1943-5487.0000705.
[16] Jin Wu, Jiansong Zhang, "Automated BIM object classification to support BIM interoperability," Construction Research Congress, pp. 706-715,2018, doi: 10.1061/(asce)cp1943-5487. 0000858.
[17] Liu Ruochen, Mu Caihong, Jiao Licheng, Liu Fang, Cheng Puhua, "Introduction to artificial intelligence," Tsinghua University Press. 2021, ISBN 978-7-302-58468-1.

AUTOMATION OF CONSTRUCTION PRODUCTION USING THE DSP METHOD

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Abstract
Mechanical engineering and industrial production are developing at an unimaginable speed with digital renaissance technology. Construction technology lags behind it, but software has been introduced into operating systems. However, the effect of digital and information technology is not very effective. The key problem is the obsolescence of the standardization and standardization of construction processes. Therefore, the dynamic structural programming (DSP) method for construction products is proposed. It is the trend of today's cyber system technology of any technological production. By combining the DSP method with Modified Gaussian S Curves (MGSC), a probabilistic mathematical iteration management of the operating system of construction products is created. This is how construction operative production fits into today's trend of modeling and simulating construction processes.

Keywords: DSP cod method, cyber system technology, modeling standardization Bill of Quantities and Bid

1. Introduction to automation

Today, all scientific branches, including organizational ones, want to be functionally connected or modeled through design information systems. This is how machine programming first developed, where each command has a machine language code. Then the lower Assemler symbolic language, which for each machine code has a symbolic code of four characters, and is converted into a machine byte code (picture X), while the instruction is defined with 64 bits. Today, however, Internet XML code has swept the world and ushered it into a digital information communication (ITC) renaissance. Thus, it becomes a system of modeling and simulation in the sphere of design, organization, and management of systems [1]. Construction uses functional modeling, which finds strength in trigonometry. Organization or system management uses various software solutions on today's large relational databases. But the organization lags in simulation and modeling behind construction and technological technology. This especially applies to construction management. Therefore, the motivation of the research is to catch up with management and design. First, in the creation of management software at the technological level and to connect them in Digital Twins [2] systems, that is, in the creation of Artificial Intelligence (AI) systems. The original problem of Leibniz and Boolean was the automation of speech, which today is experiencing a digital boom. But all the softwareization of the construction system over thirty years of management did not bring the desired profit effect in addition to the image effect. Thus, the influence of the information technology (IT) system in business has too little contribution, and it is recognized that the root of the problem lies in the low-quality definition of the construction product. That is the definition of bill of quantities documentation with outdated normative technological processes. Therefore, there is great inaccuracy in the organizational and technological processes, as well as the calculations and planning of the bid construction, that is, the process of designing the construction production. Thus, the realization cannot enter into the automation of the process.The contribution of the work is to increase the impact of IT and ITC systems on increasing the profit of the construction business system with a new model of standardization for defining the construction product. Through the new standardization of the bill of quantities and bid construction with the DSP Bill of Quantities CODE, then by modeling the norms with vector norms also defined by the DSP code, the goal is to achieve greater profit in construction systems with IT and AI systems by automation and simulations of defining the construction product by model standardization with costing and the DSP CODE as a cyber system [3] in AI technology.

2. The state of automation in construction

Automation in construction is at a low level. Especially in the sphere of production. While in the conception and design phase, she helped a lot in defining the project's task. However, in technology today, there is modeling and simulation with digital twins and BIM tool systems [4], which also enter management systems through the definition of base relational systems.

2.1. Technological softwarei

Technical software, except in the phases of conception and project definition, also entered the sphere of production. First, software was created in the realm of the main structural systems, and then in the realm of auxiliary technological constructions. This is how designer software was developed from Stress to Abacus, then architectural software from Cad to BIM tools from various manufacturers for designing products [5].

2.2. Management software

Management software is gaining weight with the development of relational databases, especially Oracle tools (Fig. 1). Large databases are suitable for data business models with entity relationship attributes (ERA) in graphic design today using the Unified Modeling Language (UML) diagram.

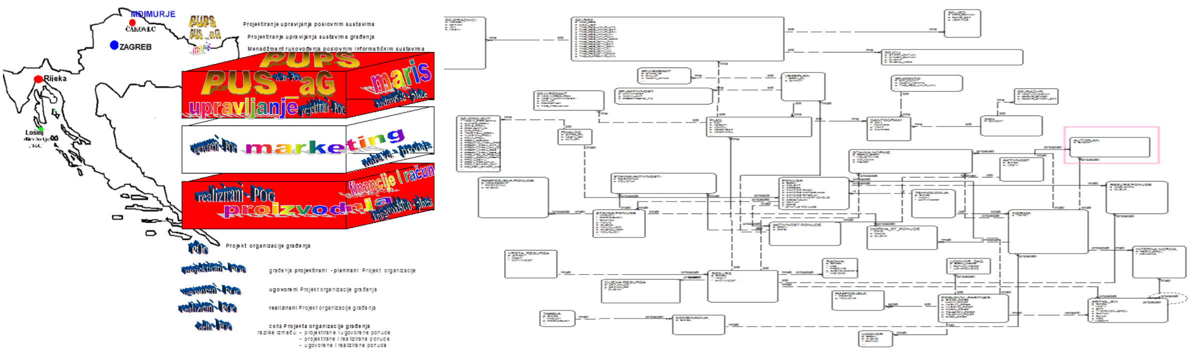

Fig. 1. Structural data model of the PUPSG application (Maris)

They enable the connection of all functions of the company in terms of accounting and production. It is production that leads to the idea of creating daily monitoring for project management. Continuing the given idea, a model standardization [6] of construction production is created, which is mostly developed to meet the needs of more precise standardization of bidding. The trend in contemporary research and within the dissertation is to achieve integrated informational project total quality management (TQM) and ranking of project success and risk criteria with daily monitoring [7] using the project management method using the modified Gaussian S-curve (MGSC) [8], which is favorable for simulations and optimization of projects. And this achieves more precise daily planning and control of the project, i.e., the introduction of "just in time" management. Of course, this enables the replacement of static POG with dynamic POG and PMD by integrating the mutual influence of norming, calculating, and planning in making an offer and implementing construction.

2.3. Cyber systems

The optimization and automation of business systems and multi-criteria decision-making create the management of expert business systems. By using the modern sciences of operational research and setting up a model in the function of the goal as a sum of states or vectors, and by systematizing them, a formula and a logical structure for creating experiential intelligence are created. However, a machine cannot be educated and cannot think abstractly like a human; the aspiration is to develop probabilities through statistical research and use combinatorics to create simulations in an analytical and visual system as an introduction to the AI system [9, 10]. Fig. 2.

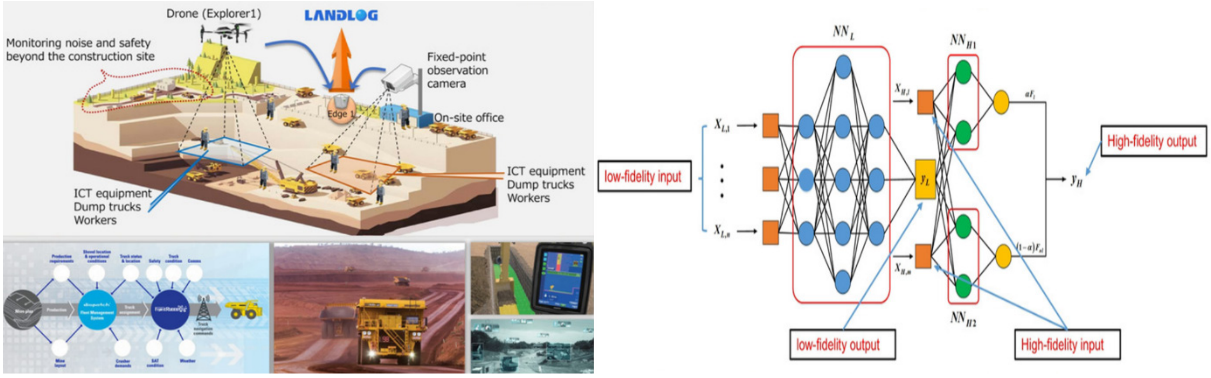

Fig. 2. (a) Digital twins in the mining industry [9]; (b) Sajber sisttem of AI sisttem [10]

The basis of automation theory is the extension of Boolean algebra to logical operators and operators for assigning a sign to a predicate that participate in the equation with sgn, i.e., heuristic graphic theories in the program implementation of the resolution-induction method and differential equations that simplify Laplace transformations or vector functionals in linear Letov problems. But simple models are based on mathematical induction and operational research as soon as the DSP method is reached.

3. DSP method of construction production

The DSP method paves the way for model standardization [11] by creating bills of quantities [12], bid constructions, and norms [13].

3.1. Moldel's standardization of the construction bid

By jointly harmonizing the description of the item in the offer, that is, the text of the bill of quantities, that is, the norm, a unique code is created for defining the construction product. A record of products is formed by levels and distribution from complex process to procedure, and the construction production record is modeled using the combinatorics and linking of these records by model standardization. Fig. 3. A record of the elements given by the project definition of the structure with a certain resource and a description of the operational elements, from activities, processes, and operations for construction production and other more advanced production to the movement of the robotization of production, the equation of the model standardization of production (MSP) (1, 2).

Fig. 3. Standardization of Activities: Elements of the Description of the Bid Construction Items [11]

$$MSP = \sum Aktivities = \sum Process = \sum Operation = \sum Procedure = \sum Movement \quad (1)$$
$$MSP = \sum projects = \sum construction = \sum resources = \sum dimension \quad (2)$$

Modular and variant components can simulate all practical processes and operations up to the procedure through CPS, MindJet graphic technology, or the software DSP method.

3.2. DSP KOD

DSP code is created by connecting dynamic programming and object or structural programming. It is very interesting because the consumption of resources can be recorded simultaneously in several processes under the condition of using the given capacity. By noting a multi-process system, it is possible to define a series of vectors x. Optimization determines which process we have to give more resources to for greater profit. In order to get that solution, it is necessary to write down all possible distributions of resources by all processes, that is, to write down and calculate all possible paths. Records can be generated using cybernetic equations (3).

$$F(X_j) = \sum_{j=1}^{n} g_j(x_j),\ S = \sum_{j=1}^{n} x_j\ 0 \le x_j \ge S \tag{3}$$

That is, by the method of recurrent equations, whose characteristic is the iteration of the functional equations of the state of the system f_n (S_n) in the sum of the observed function g_n and the function of the previous state f_(n-1) (S-x_n) with all possible changes in the value of the variables in the given functions or processes (4).

$$f_n(S_n) = max_{0 \le x_n \le S}(g_n(x_n) + f_{n-1}(S - x_n)) \tag{4}$$

For multidimensional vector dynamic programming, the equations are identical, only with more variables (x,y). The organizational differential is marked as follows: Fig. 4.

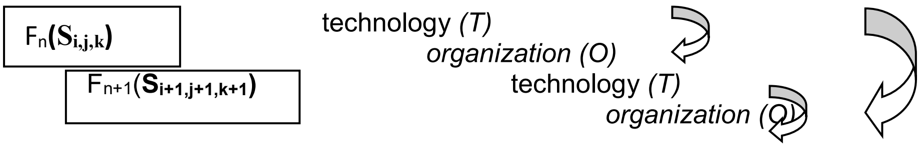

Fig. 4. DSP vector iteration organizational differential

The mathematical methods of logic and inductive optimization and the programming methods define the dual DSP structure. TREE wood plus the equation of induction, i.e., dynamic programming with object programming, defines the idea of the DSP equation for modeling the production process, i.e., construction bid construction with DSP code (5) and TROSKO code. By interconnecting and upgrading the mentioned models with iteration software technology, a DSP model was developed, which contributed to solving the problem of defining production and products. Thus, the product of the bid construction and the element of the item are defined as MSP = Σ Fn (S) = f (T,O) as a function of the record of technology (construction) and execution organization, and T ≈ O = f(A,R,D), i.e. as a function of the variables A-activities, R-resources, and D-dimensions of construction and resource performance. The greatest influence is on the standardization of the records of bid or cost-tender items as a recurrent form (5,6).

$$f_n(T_n, O_n) = f_{n+1}(T_{n+1}, O_{n+1}) \tag{5}$$

respectively $[A_{tn}[R_{tn}[D_{tn}[A_{on}[R_{on}[D_{on}]]]]]] = [A_{tn+1}[R_{tn+1}[D_{tn+1}[A_{on+1}[R_{on+1}[D_{on+1}]]]]]]$

$$= \begin{bmatrix} projekt \\ ponude \begin{bmatrix} radovi \begin{bmatrix} stavke \begin{bmatrix} Pod \\ stavke \begin{bmatrix} \mathrm{Re}\,sursi \\ konstrukcije \begin{bmatrix} kalk\_stav \begin{bmatrix} kalk\_\mathrm{dim} \\ kalk\_stav\_ekvi \end{bmatrix} \end{bmatrix} \\ \_\_\_\_\_\_ \begin{bmatrix} aktivnosti \begin{bmatrix} \mathrm{dim} \\ kalk\_akt \begin{bmatrix} kalk\_postupci\_ekvi \\ postupci \begin{bmatrix} kalk\_post\_ekvi \\ resursi \begin{bmatrix} kalk\_norma\_res \\ satnica\_(satnica, R, M, S) \end{bmatrix} \end{bmatrix} \end{bmatrix} \end{bmatrix} \end{bmatrix} \end{bmatrix} \end{bmatrix} \end{bmatrix} \end{bmatrix} \end{bmatrix} \end{bmatrix} \tag{6}$$

The statistical MGSC method and the method of least squares and the method of structural modeling and combining are used to optimize the creation of a bid construction.

3.3. MGSC u DSP projects

In recent times, probabilistic forecasting of project performance and the use of stochastic S-curves with a program package for generating stochastic S-curves and a simulation approach have defined the dispersion deviation of the MGSC project's finances and time as a function of the density distribution of costs and time. Diagrams of expected monetary value (EMV) or S diagrams are popular today and supplemented with functional 3D-MGSK [14] (7), Fig. 5.

$$skvGr(x,T) = \lambda kv \cdot \int_0^x \frac{1}{(a \cdot T + b) \cdot \sqrt{2 \cdot \pi}} \cdot e^{\frac{-(x-\mu)^2}{kv \cdot (a \cdot T + b)}} dx \tag{7}$$

The leveling and matching of the curves, i.e., the modification of the Gaussian curve, refers to the introduction of a constant kv parameter in the value of 10,000 units.

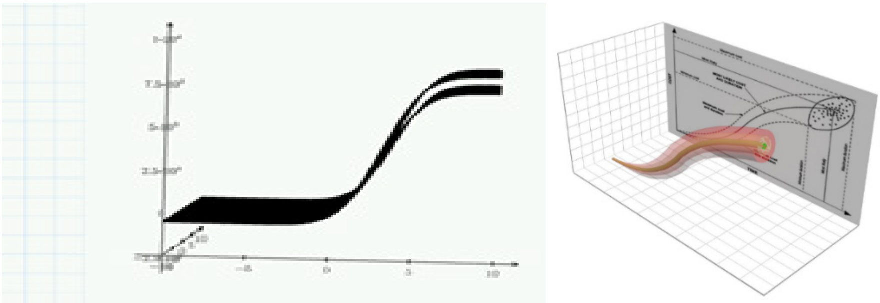

Fig. 5. Simulation project management using MGSC (Mathcad and Solidworks) tools

By further supplementing the DSP method by planning a three-iteration record of permutations and variations, the form of the equations shows the software code of loops over the variables within the matrix structure, which does not have standard mathematical characteristics but software mathematics.

3.4. Combinatorics in the DSP bid construction

Creating a record of all Croatian lottery combinations opens the way to defining permutations, variations, and combinations in a few minutes given by equation (8). Such combinatorial iterative equations are suitable for computers. Permutations can also be shown graphically by adding the next number to all intermediate columns and the first and last columns of the previous record. A software iterative equation defines a series of records of all combinations or variations using a matrix representation [15].

$$K = U\left[\begin{matrix} n_1 \to k_{max} - 1 \\ n_{max} \hookleftarrow \end{matrix} U\left[\begin{matrix} n_2 \to 1 \\ n_1 - k_i \hookleftarrow \end{matrix} U\left[\begin{matrix} n_i \to n_i + 1 \hookleftarrow n_k - 1 \\ n_1 - k_i \hookleftarrow \end{matrix} U\left[\begin{matrix} n_k \to n_1 + 1 \\ n_{max} \hookleftarrow \end{matrix}\right]\right]\right]\right] \tag{8}$$

Today, Mathcad has also greatly developed, and it can also graphically write matrices using software mathematics, so that such matrices or determinants can be called software matrices.

4. Conclusion

The new model standardization for defining the construction product of the bid construction with the DSP costing code in mind is slow, but it provides more precise normative data for defining the planning and calculation of the project. This requires a new model for standardization of norms with the vector form of VN-KOD norms [16] defined by the DSP code. This gives more precise specifications for resources in production. DSP in terms of norms and bills of quantities replaces the component of the norm and bill of quantities in a classic way and enables the automation of construction products from project documentation to production, which enables chipping of the construction bid, i.e., the design bill of quantities. By systematizing and synthesizing, such waste VN-CODE can be returned to the normative base, thus creating a model standardization base of norms. At the same time, this norm becomes the basis for unit calculations and the basis for the new definition of product certificates directly from the normative structure. Finding and modeling the functional dependencies of a certain type of work opens a continuous process of modernization and standardization of standardization. Further filling of the database of construction site data and their processing leads to optimal results. As for the time component of the work resource, it can be modeled in function with designer equations, mechanical and other scientific achievements, or equations for the material or machine normative values of the resource. In connection with structural programming as a great support for modeling, we turn the classic static normalization into a dynamic one. With this DSP modeling, we can make an organizational leap in technological development by defining the organizational differential. It is a path to AI systems and a great contribution of digitization to daily management, i.e., the creation of profit within software-mathematical organizational problems. Which leads to system automation [17] at the system level of physical processes and controls and the establishment of smart project management [18] with the aspiration to define AI [19] with simultaneous management. Thus, Android technologies communicatively unify the concept of the fourth industrial revolution through the cloud of the Internet and virtual technology [20].

References

[1] M. A. Musarat, M. Altaf, M. B. A. Rabbani, and K. M. Alzub, “Innovation in Construction: A new norm against Traditional Construction“, International Conference on Data Analytics for Business and Industry (ICDABI), 2022, DOI:10.1109/ICDABI56818.2022.10041472

[2] G. Ryzhakova, O. Malykhina, V. Pokolenko, O. Rubtsova, O. Homenko, I. Nesterenko, and T. Honcharenko, “Construction Project Management with Digital Twin Information System“, International Journal of Emerging Technology and Advanced Engineering Website, 2022, DOI: 10.46338/ijetae1022_03 19

[3] S. Ruiz-Arenas, Z. Rusak, R. Mejia-Gutierrez, and I. Horvath, “Implementation of system operation Modes for Health Management and Failure Prognosis in Cyber-Physical systems“, Sensors, 2020, www.mdpi.com/journal/sensors/doi:10.3390/s20082429

[4] A. Istanbullu, S. Wamuziri, and M. Siddique, “BIM Digital twins environment to enhance construction process“, IOP Conf. Series: Earth and Environmental Science 1055, 2022, doi:10.1088/1755-1315/1055/1/012006 1

[5] T. Teschemacher, and K-U. Bletzinger, CAD-integrated parametric modular construction design, Engineering Reports Wiley, 2022, DOI: 10.1002/eng2.12632

[6] V. Križaić, “System adjustments through vector organization and technology“, Creative Construction Conference, 2019, str. 440-445 doi:10.3311/CCC2019-061

[7] V. Križai, D. Hranj. *Daily monitoring by IIS*, 11th International Conference Organization Faculty of Civil Engineering, 2013, str. 26-26

[8] V. Križaić, and D. Hranj, “Project Planning by Modified Gauss S-Curve“, Creative Construction e- Conference, 2020. str. 65-70 doi:10.3311/CCC2020-047

[9] M. Servin, F. Vesterlund, and E. Wallin, “Digital Twins with embedded particle simulation“, 14th World Congress in Computational Mechanics (WCCM) ECCOMAS Congress 2020, 2021, 2965, doi:10.23967/wccm-eccomas.2020.309

[10] X. Zhang, F. Xie, T. Ji, and Z. Zhu, “Multi-fidelity aerodinamic optimization using deep neural network“, 14th World Congress in Computational Mechanics (WCCM) ECCOMAS Congress 2020, 2021, doi:10.23967/wccm-eccomas.2020.309

[11] V. Križaić, and I. Završki, “Modelska standardizacija građevinske ponude metodom dinamičko strukturnog programiranja“, 5. Simpozij doktorskog studija građevinarstva 2019, 2019, DOI: https://doi.org/10.5592/CO/PhDSym.2019

[12] Liu, K. (2022), Research on Construction of Bill of Quantities of Prefabricated Buildings Based on BIM, *Journal of Architectural Research and Development,* 6(5):25-30, DOI:10.26689/jard.v6i5.4259

[13] Zaki, T., Magdy, A., Nassar, K. (2020), BIM-Based Bill of Quantities Generator following POMI and NRM2 Methods of Measurement, *ResearchGate*, https://www.researchgate.net/publication/342625082

[14] V. Križaić, T. Rodiger, and S. Baksa, “Simulacijsko upravljanje projektima pomoću Modificirane Gaussove S-krivulje“, 14th World Congress in Computational Mechanics (WCCM) ECCOMAS Congress 2020, 2021, doi:10.23967/wccm-eccomas.2020.309

[15] V. Križaić, D. Hranj, and T. Rodriger, “Utjecaj softverske matematike na modeliranje u graditeljstvu“, 5. međunarodna konferencija INOVACIJE, TEHNOLOGIJE, EDUKACIJA I MENADŽMENT, 2018, chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/https://konferencija.mev.hr/wp-content/uploads/2018/04/5.-me%C4%91unarodna-konferencija-ITEM-%E2%80%93-Zbornik-radova-1.pdf

[16] V. Križaić, *Application of Norms Models with Vectoral System in Construkction Projects,* Journal of Civil Engineering an Architecture USA, 2014, 2014, DOI: 10.17265/1934-7359/2014.06.007

[17] O. C. Madubuike, and C. J. Anumba, “Potential for the Integration of Cyber-Physical Systems with Intelligent Buildings“, Researchgate, DOI: 10.1061/9780784482865.074

[18] I. Horvat, “Connectors of smart design and smart system“, Artificial Intelligence for Engineering Design Analysis and Manufacturing,2021, https://doi.org/10.1017/S0890060421000068

[19] B. Naticchia, L. Messi, M.Pirani, A. Bonci, A. Carbonari, and L.C. Tolve, “Holonic System for Real-Time Emergency management in Buildings“, ResearchGate, 2018, https://www.researchgate.net/publication/333894832

[20] M. Nogel, G. Kovach, and G. Wersenyi, “he Regulation of Digital Reality in Nutshell“, ResearchGate, 2022, https://www.researchgate.net/publication/354689836

CONCEPTUAL DESIGN USING BIM OF ULTRA-HIGH-SPEED CONSTRUCTION SYSTEM ASSUMING EMERGENCY SITUATIONS

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Abstract

The Japanese construction production system has aimed to achieve a high degree of balance between high Q: quality, low C: cost, appropriate construction D: duration, S: safety assurance, and reduction of E: environmental impact in project results. Against the background of low economic growth and low interest rates after the bursting of the bubble economy, the Japanese client did not strongly demand "UHSCS: ultra-high-speed construction system," which is the purpose of this research theme. However, if the QCSE satisfies the required standard, it is obvious that the introduction of UHSCS that realizes early recovery of funds will increase the value of the project. In addition, it goes without saying that reducing time, which is a parameter for amount of labor, material, and indirect costs, is effective in improving productivity, which the Japanese construction industry is currently working on. During the recent spread of COVID-19, those of us involved in construction watched helplessly as lives and health were lost due to the lack of medical facilities. In Wuhan city, China, a medical facility with 1,000 beds is said to have started operating 10 days after the site was prepared. In China, which is undergoing economic growth and has high financing costs, there was a strong need for UHSCS for hotels and offices. Based on the current situation, it is necessary to review UHSCS as another form of building production. The international architectural society has a social mission to prepare for the occurrence of similar pandemics and disasters such as earthquakes directly hitting the Tokyo metropolitan area that are predicted to occur in the future. This research utilizes the excellent construction elemental technology of Japanese industry, BIM, IoT, SCM and robotics, and presents a conceptual design of an UHSCS based on thorough standardization and labor-saving construction.

Keywords: BIM, facilities for emergencies, robotics, SCM, ultra-high-speed construction system

1. Research background

1-1. Acceleration of construction production workflow

In construction production in Japan, we have aimed for a balance of high Q: quality, low C: cost, appropriate construction D: duration, S: safety assurance, and reduction of E: environmental impact in project results. During the recent spread of COVID-19, those of us involved in construction watched helplessly as lives and health were lost due to the lack of medical facilities in Japan. Meanwhile, according to reports, a 1,000-bed medical facility in Wuhan, China, began operations 10 days after site preparation. In China, which is undergoing economic growth and has high financing costs, there was a strong need for "UHSCS: ultra-high-speed construction system," for hotels and offices. Against the background of low economic growth and low interest rates after the bursting of the bubble economy, the Japanese client did not strongly demand UHSCS which is the purpose of this research theme. Based on the current situation, it is necessary to review UHSCS as another form of building production. The international architectural society has a social mission to prepare for the occurrence of similar pandemics and disasters such as earthquakes directly hitting the Tokyo metropolitan area that are predicted to occur in the future. However, it goes without saying that even in normal times, "speeding up" is a major factor in improving business feasibility.

1-2. Previous research

This research team has focused on the "group" function as a structural characteristic of BIM. BIM has two environments: a so-called "factory" environment where objects are created and a "site" where building models are created. In the "factory" environment, it is possible to create nested "groups" that are the very structure of the supply chain. Preparing the "factory" product in advance shortens the construction period compared to making a single part, but the same can be said for BIM. As pointed out in previous research, in digital space BIM, for example, it is possible to create a "group" that does not stand on its own in reality, taking out only the space and surface finishing materials. This "imaginary group", which the research team calls a "design study unit", can also be made ready-made in advance, contributing to shortening the study period at the time of study. When using the "design study unit", it is also possible to simplify the category classification once, improve the operability during study, and replace it with the BIM native category again using programming after the study is completed. [1]

2. Purpose of research

The purpose of this research is to show the procedure for speeding up the construction production workflow, using the structural characteristics of BIM, using the hospital facility production under emergency situations as a specific subject.

3. Research method

Autodesk Revit 2022 (hereinafter referred to as Revit) was used as the BIM core software, and the visual programming tool Dynamo and data integration software Navisworks were used together.

The examination method is based on the following steps.

- Consideration of workflow
- Consideration of classification of hospital functions and unit method
- Creation of BIM model and unit cataloging
- Development of zoning study method and unit automatic placement method
- Replacement with design study unit and examination of parts
- Consideration of the above method

4. Research content

4.1. Consideration of Workflow

While comparing it with the general workflow, we considered speeding up at each stage of design, production design, and construction.

- Speeding up the design stage

Unit models of typical functional units are prepared in advance and organized as a " Catalogue " to expedite consideration.

- Speeding up the production design stage

Accelerate the study of unitization and parts by using the "design study unit" that makes it easy to adjust design, structure, and equipment at the same time.

- At the construction stage

Accelerate on-site work by utilizing prefabricated units that integrate design, structure, and equipment.

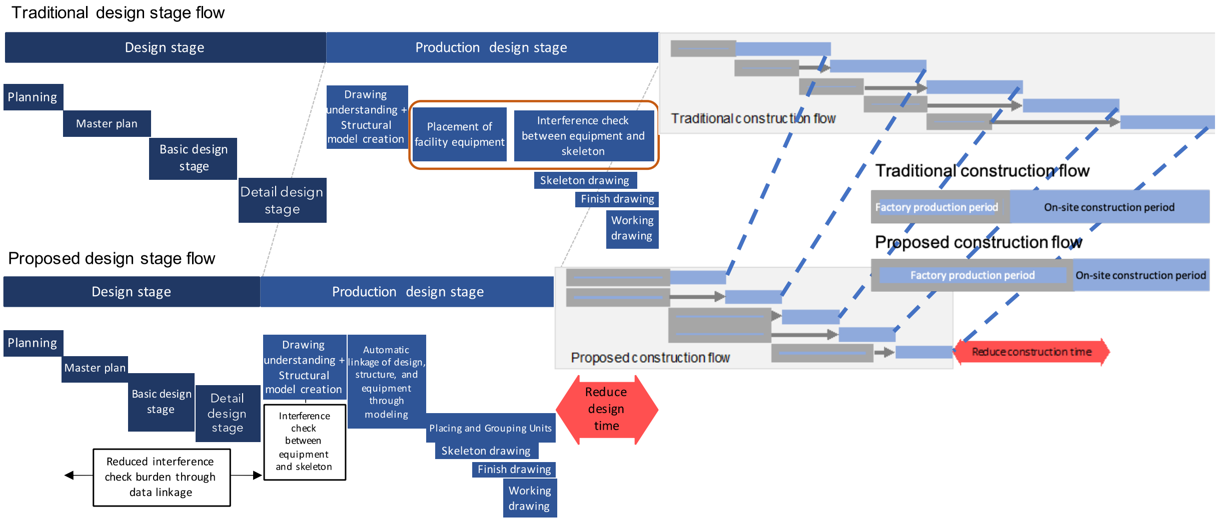

Fig. 1 Examining a workflow that achieves "higher speed"

4.2. Consideration of classification of hospital functions and unit method

Based on the organization of hospital zoning and traffic line plans, a "center corridor" was established to consolidate the main traffic lines and main equipment routes in order to simplify the functional configuration of the building. The center corridor becomes the "trunk" and each functional zone becomes the "branch and leaf", making the hospital structure extremely clear as a tree-like organization.

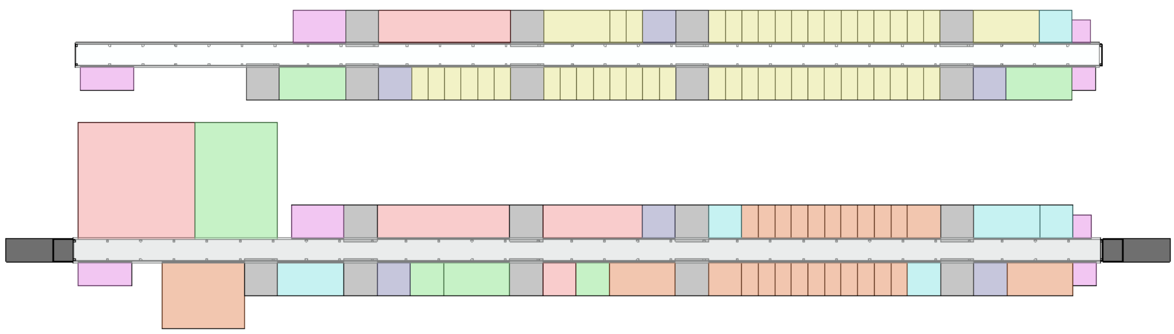

Fig. 2 Center corridor and functional zones (The top picture is the 1st floor, the bottom picture is the 2nd floor.)

4.2.1. Center Corridor

The center corridor has the following three functions,

- Line of flow as a “trunk”

Hospital functions can be broadly divided into outpatient flow lines and back flow lines. The traffic line of foreigners is set as the center corridor. Through this arrangement, it is possible to realize a universal design that makes it easy for even first-time visitors to intuitively grasp the flow line. Zones are also clearly demarcated, contributing to security planning.

- Equipment route as a “trunk”

The main trunk line for electrical equipment and the main trunk line for water supply and drainage were consolidated in the center corridor. In general building plans, water supply and drainage routes are not necessarily connected to a single main trunk, but water is often supplied for each zone and sent to an underground pit through vertical pipes for each zone, but the piping and wiring are network-like. It becomes a plan, and the number of design adjustments increases. The tree-like organization greatly reduces the number of items to be coordinated between buildings and facilities. Although there is a disadvantage that the wiring and piping length increases slightly, the advantage of speeding up was given top priority.

- Seismic element as a trunk

In the center corridor, earthquake-resistant braces (X direction Y direction braces and horizontal braces) are installed to provide sufficient strength against rolling, and the center corridor partially bears the horizontal force of each functional zone during an earthquake. plan to As a result, the degree of freedom in planning for each functional zone can be increased, and the speed of structural design can be increased. Although there is a disadvantage that the frame of the center corridor is slightly excessive, the advantage of speeding up is given top priority here as well.

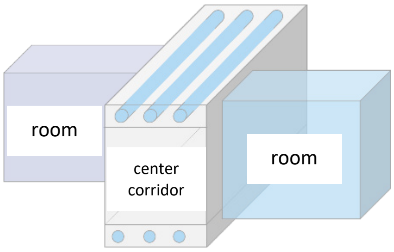

Fig. 3 Center corridor and functional zones as "trunk"

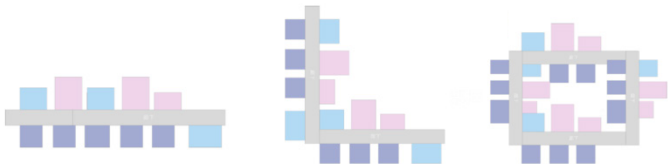

Fig. 4 Plan variations

With the above arrangement, for example, it is possible to partially complete the construction of the center corridor and patient rooms first and then start using them. Furthermore, it is also possible to extend the center corridor in the future and expand the function. It can be said that it is a horizontal development of the old concept of "metabolism".

4.2.2. Plan variations

In actual planning, if the center corridor is set in a straight line, depending on the scale, there will be an adverse effect of lengthening the back flow line of doctors and nurses. By considering the following plan variations, it is possible to shorten the back flow line.

4.3. Creation of BIM model and unit cataloging

Unitization of zones requires a unit that can be unitized into a container for each room like a hospital room, and a complex functional linkage like an operating room. Unitization on BIM that cannot be done as a unit was divided and organized. Design, structure, and equipment BIM models were created based on the standard plan, and grouped using the group function. I also entered the specification information such as performance. In order to make it easier to refer to, the created "group" was arranged in the project space of BIM and made a "catalog". When designing, copy from this catalog and use it while transforming, supplementing and correcting information according to the project. In addition to the zone catalog, we also prepared a study model using a spatial object called a Revit "mass". At the initial stage of design, the volume model is used to expedite zoning studies, and once the zoning plan has been finalized, it is replaced with the zone model. It is automated using programming, and multi-objective optimization is also utilized for site layout studies.

4.4. Development of zoning study method and unit automatic placement method

The design study unit was used in the study of unit construction and prefabrication. By temporarily replacing models with a single category, it becomes easier to divide and integrate design, structure, and equipment models, and it also speeds up the examination of parts. The attribute information necessary for construction is once extracted to Excel, and after converting it into parts, it is put back into the native data. The BIM model created in this way was linked to Navisworks, and the on-site process was examined using the 4D simulation function. Fig. 7 shows the process of the study. In Fig. 8, the model created this time was visualized by linking it with the landscape software Lumion.

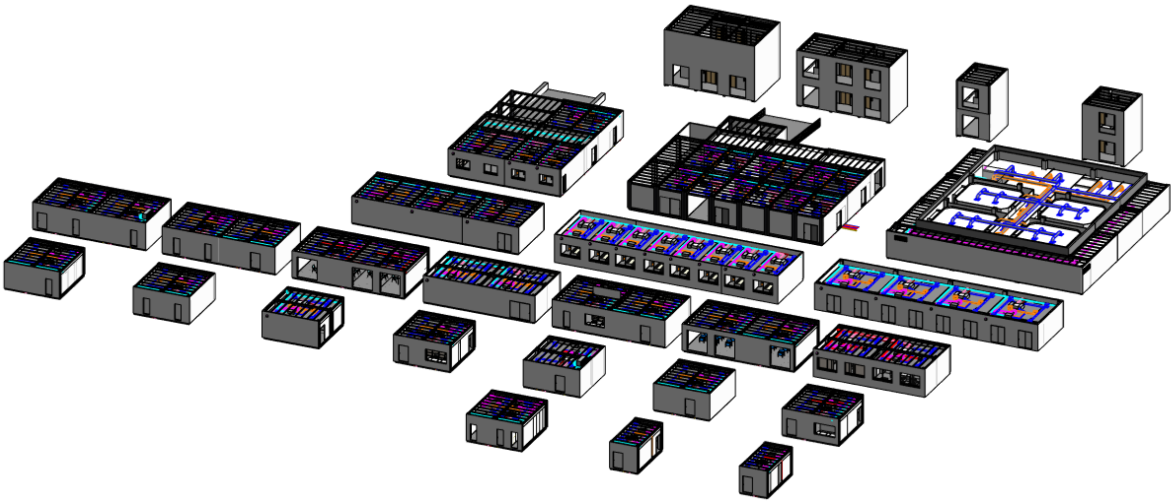

Fig. 5 Maintained zone model catalog

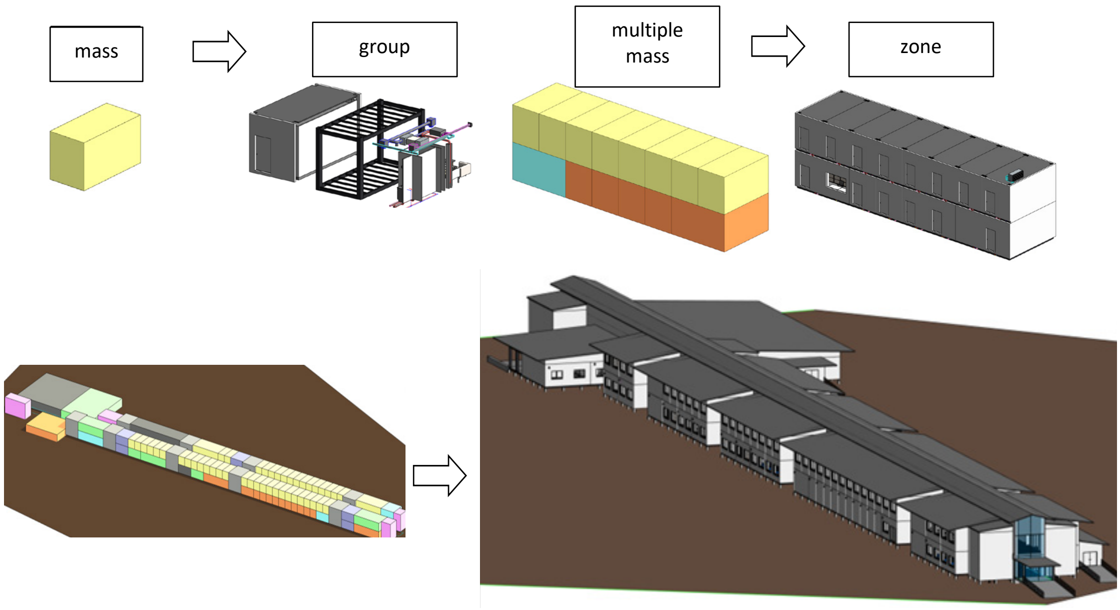

Fig. 6 Initial study model and model replacement

5. Discussion

In this paper, assuming "emergency situations" such as disasters and pandemics, we focus on medical facilities with high priority on functionality, and use the concept and function of BIM to construct buildings such as spaces, members, and units. The concept of UHSCS with simplified elements is presented. Specifically, it showed a rational design using BIM, the introduction of prefabrication that is compatible with the concept of BIM, and the procedure for speeding up the workflow by saving labour at the construction site. I would like to think about the effect of compensating for the construction production system, which is understaffed even in normal times, by thoroughly standardizing and labour-saving construction trials by further utilizing BIM, IoT, SCM, robotics, etc., which are building elemental technologies of the Japanese industry.

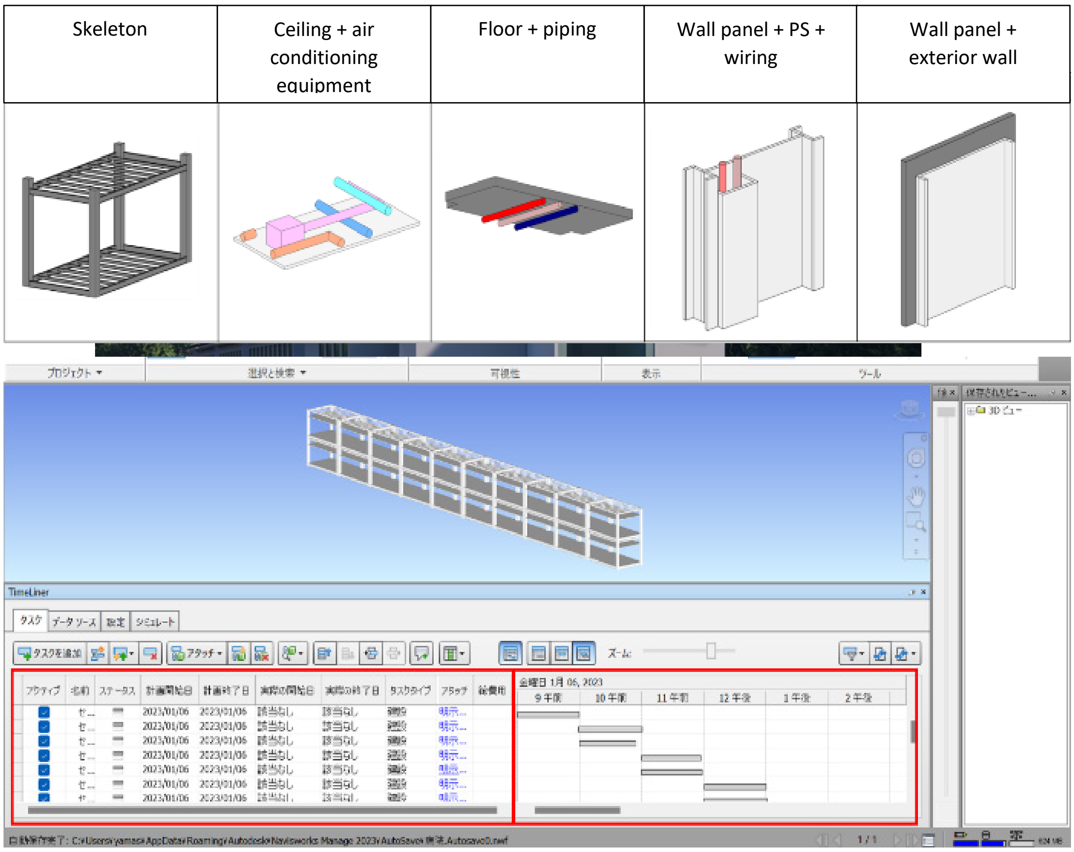

Fig. 7 Construction parts and 4D simulation

Fig. 8 Scenery simulation

References

[1] ENDO Kazuyoshi, BOCK Thomas, LINNER Thomas, “Rapid return on investment by innovative methods in construction visualized by cash flow model, Proceedings of Creative Construction Conference 2013, Budapest, Hungary, July 6–9, 2013

[2] OKADO Satoshi, ENDO Kazuyoshi, IWAMURA Masato, “Research on construction period examination at the initial stage of basic design using BIM, 36th Proceedings of Symposium on Building Construction and Management of Projects of AIJ (in Japanese), pp. 233-238, 2021

[3] IWAMURA Masato, ENDO Kazuyoshi, SATOSHI Okado, “Attempts of production design using BIM in construction projects, part 2 Examination of productivity improvement by unitizing BIM objects for design process,” 2021 Summaries of technical papers of annual meeting of AIJ(in Japanese). , pp. 109-110, 2021

[4] ENDO Kazuyoshi, IWAMURA Masato, OKADO Satoshi, “Attempts of production design using BIM in construction projects Part 1 Examination of productivity improvement by unitizing building parts and elements,” 2021 Summaries of technical papers of annual meeting of AIJ (in Japanese). , pp. 107-108, 2021

[5] JISHIZU Yuko, “Computational BIM and with Dynamo+Revit,”, 1st printing, Tokyo: Japan, BNN (in Japanese), 2022, ISBN: 978-4-8025-1210-7

DEEP REINFORCEMENT LEARNING DRIVEN AUTONOMOUS FLIGHT UAV FOR CONSTRUCTION PROGRESS MONITORING

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Abstract

Recently, Unmanned Aerial Vehicles(UAV) have been studied as a means of monitoring construction sites more safely and accurately. However, construction sites are complex environments with numerous heavy equipment and workers constantly moving around, making it difficult to predict obstacles and anticipate changes. To use UAVs for on-site monitoring in such environments, a control algorithm that can adapt to changing conditions is required. Therefore, this study proposes a reinforcement learning-based autonomous drone algorithm. UAVs, obstacles, and target points are positioned in a 3D learning environment, and random movements are assigned. The UAV detects objects using LiDAR sensors and assigns penalties if it collides with an obstacle, while rewarding if it reaches a target point. Through this method, the autonomously driven UAV trained using the proposed algorithm demonstrated similar accuracy to the existing GPS-based autonomous driving algorithm and up to 50% shorter average time to reach the target point, highlighting its high potential for practical use.

Peer-review under responsibility of the scientific committee of the Creative Construction Conference 2023.

Keywords: Autonomous Flight, Unmanned aerial vehicles (UAVs), Progress Monitoring, Deep Reinforcement Learning, Proximal Policy Optimization.

1. Introduction

The use of unmanned aerial vehicles (UAVs) for monitoring and data collection in construction sites has recently gained significant attention. UAVs have been utilized in various fields, such as military reconnaissance, education, and training, since their experimental deployment during World War I. Since 2016, the UAV market has seen increased consumer demand, growing from a $2 billion market in 2016 [1] to a $22.5 billion market in 2020 [2]. Compared to traditional monitoring methods that rely on workers or equipment, utilizing UAVs for monitoring construction site provides a safer alternative for accessing hard-to-reach areas, such as high places and narrow spaces. UAVs can also be programmed to fly autonomously, including their flight path, speed, and altitude, reducing the need for human intervention and effectively reducing the time and labour costs associated with traditional monitoring methods where workers reach target points, take photos, return, and inspect and report the photos. For this reason, applying UAVs in construction sites is an essential technology for improving safety and productivity in future construction sites. UAVs can provide real-time data and imagery to construction sites managers, enabling them to make informed decisions quickly, identify potential hazards, and prevent accidents. As a result, UAVs have the potential to revolutionize the construction industry, making it safer, more efficient, and more cost-effective.

On the other hand, the construction site environment is characterized by a high degree of uncertainty due to the movement of numerous heavy machinery and workers, as well as the daily progress that brings constant changes. Such an environment makes challenging control problems for the UAV operator. The operators should manually see the surrounding environment and control the UAV to avoid obstacles (e.g., walls, columns, temporary facilities) while finding the optimal locations for target monitoring. That is labour intensive, time consuming and costly, which interferes the adoption of UAV in construction site. For these reasons, it is imperative to fully automate UAV monitoring through autonomous flight from the take-off point to the target area without any human intervention, allowing for reliable target monitoring.

However, current autonomous UAV relies on the use of global positioning system (GPS) and other external sensors to estimate location. Previous research has achieved autonomous UAV flight by forcing the UAV to move in a way that avoids obstacles detected based on light detection and ranging (LiDAR) sensors or GPS-based information, to prevent the UAV from approaching obstacles within a certain distance. Additionally, autonomous driving using a convolutional neural network called DroNet, which predicts the probability of collisions and steering angles simultaneously based on driving data of vehicles that comply with traffic regulations, such as cars and bicycles, has also been studied. However, these methods are difficult to apply to the development of autonomous UAVs for construction progress monitoring, due to the unique and random nature of obstacles present on construction sites. These existing approaches are insufficient in quickly responding to unpredictable and random obstacles encountered on construction sites.

Therefore, to implement a UAV that can efficiently explore obstacles and reach the destination on construction sites, it is necessary to implement various abilities such as 1) real-time obstacle detection with rider and avoidance, 2) recognizing target locations for enabling the autonomous UAV to perform tasks such as arriving at a specific location or performing a task (e.g., image capture, record videos) at that location, and 3) finding optimal traveling path. To realize the abilities above, we suggest the reinforcement learning, a machine learning training method based on rewarding desired behaviors and/or punishing undesired benaviors. To apply reinforcement learning to autonomous UAVs, we created a virtual, dynamic construction sites environment where human worker objects are randomly moving, then we put a virtual UAV in it attached with a hypothetical LiDAR sensor. Then, we tested whether the UAV could learn an autonomous flight strategy (i.e., avoiding obstacles, recognizing target locations, and finding optimal traveling path) without human intervention in the dynamic construction sites environment.

The structure of this paper is as follows. In section 2, we review related works to find the research gaps, then explains research objective and method in section 3. Then we design a case study in section 4 and analyze the experiments in section 5. Finally, we conclude our paper in section 6.

2. Related Works

2.1. Literature review

2.1.1. Progress monitoring in traditional construction sites

In the case of large-scale construction projects, there are various factors that make it difficult to monitor the project's progress and processes. These factors include 1) remote construction sites, 2) the large size of construction sites, 3) the need to manage rapidly changing processes, 4) difficulty accessing certain areas, and 5) insufficient personnel. Traditionally, workers or managers have used methods such as taking photos of the site to assess the progress later or using CCTV footage to monitor real-time progress. However, these methods have limitations, such as restricted access to certain areas when taking photos and difficulty capturing footage from various locations due to fixed camera positions.[3] Moreover, construction sites are often very large in scale and have scattered workspaces, making it difficult to regularly monitor every corner of the project with limited personnel. [4] In some cases, additional devices such as Inertial Measurement Units (IMUs), GPS, Ultra-Wide Band (UWB), and RFID are being used effectively to monitor workers or equipment. However, the widespread use of these devices is facing challenges due to the increased cost of installation and monitoring, as well as discomfort and resistance from workers due to the attachment of devices to their bodies. [5]

The technology and methods that have been proposed or developed for on-site work monitoring have often encountered problems with worker compliance or practical application in construction sites. In contrast, research on the application of unmanned aerial vehicles (UAVs) for site monitoring has shown promising results. To address issues such as difficulty of access and insufficient personnel in project monitoring, the use of UAVs for progress monitoring has been proposed. [6-11]

2.1.2. Application of unmanned aerial vehicles (UAVs) for progress monitoring in construction

Several review papers examined the use of UAVs in construction progress monitoring, demonstrating how 2D images captured by UAVs can be matched to geographic information to create 3D models. Basic 3D models include point cloud models and digital elevation models (Figure 5), and these models can be transformed into 3D models in a BIM environment using Scan-to-BIM techniques. Research on process and quality management through the comparison of as-built and as-planned models in a BIM environment has also been conducted [7-9]. As mentioned earlier, the 2D image and 3D spatial information obtained from UAVs are often used in conjunction with BIM models. Recently, augmented reality (AR) techniques have been developed in conjunction with BIM models and UAVs to monitor the progress of construction projects and provide workers with intuitive access to related information [10]. Another study on the application of UAV technology for construction site monitoring [11] focused more on the use and analysis of photos and videos taken by UAVs rather than on the capabilities of the UAVs themselves. This study was not about UAVs, but rather about the data obtained through the use of UAVs.

Furthermore, research is actively being conducted on utilizing machine learning to automatically transform objects by identifying their characteristics in the Scan-to-BIM process. Additionally, there are studies being conducted on incorporating UAV guidance devices into BIM models [12]. Currently, guidance devices adopt a method of setting and controlling UAV flight plans using general satellite maps such as Google Maps, but this has limitations in reflecting the progress of construction projects in a timely manner. In other words, if information on structures that have not been reflected in satellite maps is not reflected in the flight plan, this can not only cause collisions between structures and UAVs, but also lead to secondary accidents. The need for subsequent research to address these issues has been mentioned. In these studies, problems with the path designation of UAVs and the need for autonomous driving are commonly mentioned. Therefore, we found the need for research on autonomous UAVs for application in construction sites.

2.1.3. Development of autonomous UAVs based on deep learning.

Recently, deep learning-based approaches have been proposed to successfully apply autonomous UAVs. Deep learning methods can be broadly categorized into supervised learning, unsupervised learning, and reinforcement learning. Among these, supervised learning is actively applied for autonomous UAVs. In supervised learning, a UAV can learn how to drive by mimicking the pilot's flight style, who demonstrates optimal flights in an experimental environment. This approach is also known as imitation learning or behavior cloning and is widely used in autonomous UAV technology. However, applying this technology to monitor construction sites is remained challenging. To create a dataset of optimal flight for the model to reference, many test flights must be conducted in a controlled environment. However, in the construction sites environment where site conditions are changing over time, it is difficult to create enough and reliable flight data. Therefore, to teach autonomous flight in a construction sites environment, reinforcement learning can be a useful machine learning approach. Reinforcement learning is a method for sequential decision-making in which the agent and the environment interact to select actions that maximize reward among actions that can be taken in the current state. [13]. This approach is characterized by learning the value of each choice in every situation by trial and error in an unknown environment without prior knowledge, receiving rewards or penalties for actions, and gradually learning through the process. [14]

reinforcement learning has the characteristic of learning the value of each action in each situation by experiencing trial and error in an unknown environment without prior knowledge, receiving rewards or punishments for actions, and continuously making decisions on which action to take to achieve the goal in each situation. As a result, the learned outcome of reinforcement learning is better able to adapt to sudden variables or unexpected situations. Rather than commanding movement based on predetermined rules, paths, or actions, reinforcement learning constantly makes decisions on which actions to take in each situation to accomplish the goal, making it robust to sudden environmental changes. Therefore, it is believed that reinforcement learning for training autonomous UAVs will enable stable flight in construction sites environments, which are always changing and have many variables. This paper aims to develop autonomous UAVs that can be effectively applied to construction sites by applying reinforcement learning to autonomous driving learning.

3. AUTONOMOUS FLIGHT UAV FOR CONSTRUCTION PROGRESS MONITORING MODEL

3.1. Research objective

The goal of this study is to develop a construction progress monitoring autonomous UAV that is tailored to the characteristics of construction sites environments. We propose a reinforcement learning-based autonomous driving model that can navigate through moving workers, changing environments, and multiple target points, and validate it by comparing it with existing GPS-based navigation autonomous driving.

3.2. Framework overview

The framework of this study is as follows: 1) creation of a 3D model that includes an environment with obstacles mimicking a construction sites, targets for image capture, and randomly moving workers, as well as the UAV that is the subject of the learning, and 2) extraction and performance evaluation of an autonomous driving model through reinforcement learning in the created environment.

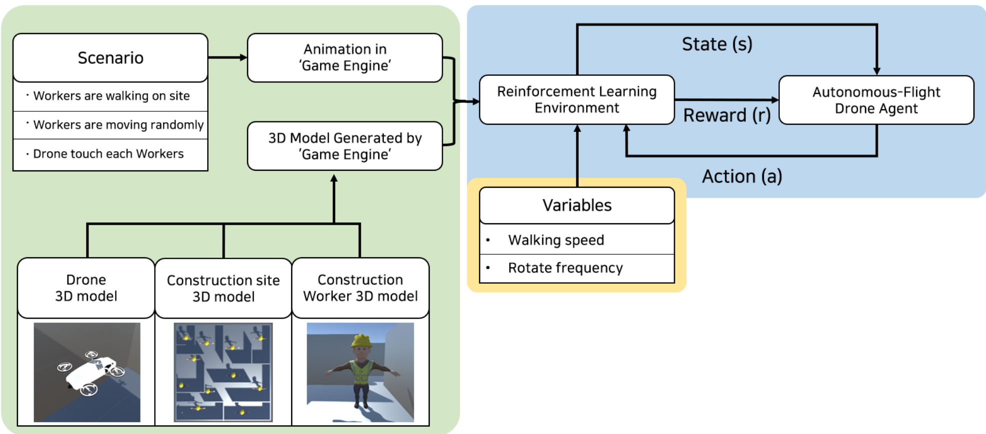

Fig. 1. Process for Reinforcement Learning driven autonomous flight UAV algorithm

3.3. Research method

The rule used by the agent for selection in reinforcement learning is called a policy, and research on finding the optimal policy is divided into two main types: value-based algorithms and policy-based algorithms [15]. Our reinforcement learning uses the PPO (Proximal Policy Optimization) algorithm, a policy-based reinforcement learning algorithm from the ML_Agents module built into Unity. PPO introduces a clipping function that limits policy updates instead of the KL Divergence constraint, and it is widely used in many reinforcement learning studies for autonomous vehicles, UAVs, etc. due to its high performance and reduced computational complexity [16][17].

In reinforcement learning, a reward is a short-term metric used to evaluate how effective the agent's actions are in the current state. The agent learns to behave in a way that maximizes the cumulative reward until the episode is complete. Therefore, designing appropriate rewards is crucial to achieving the goal. In this study, we first use LiDAR sensors to allow the UAV to explore surrounding objects. If an obstacle is detected, a penalty is imposed based on the distance, and if a short distance that could lead to a collision with the UAV is measured, the episode is terminated, and a penalty is imposed. After the episode ends, the rewards and penalties obtained from that episode are summed up, and the agent chooses the next action that can result in a better reward.

4. Case Study

To realize our research objective, we conducted a case study to verify whether autonomous UAVs trained with reinforcement learning can achieve better autonomy in dynamic construction sites environments than traditional navigation algorithms. We created a 3D virtual construction sites environment using game engines and placed worker models that move randomly. We trained autonomous driving algorithms in such an environment. Finally, we evaluated the performance of the UAV trained with reinforcement learning with a UAV using location-based navigation system, which is a basic module built into the game engine.

4.1. Case scenario

This case study aims to compare and validate whether a UAV trained with reinforcement learning can perform better autonomous flights in dynamic construction sites environments than a UAV using traditional navigation algorithms. To create an environment that reflects the dynamics and uncertainties of a construction sites, we used the Unity, a 3D game engine, to construct a 3D environment for the UAV to navigate. To create a dynamic construction sites environment, we created structures in a large flat space, separating the space with 13 walls. We placed 11 worker models in that space and added a movement script to give the workers randomized movements, thereby adding randomness to the environment. The workers rotate randomly between 0-360 degrees clockwise and move forward every 2 seconds or when they collide with a wall (obstacle). Moreover, we experimented with various workers' movement speeds to observe the autonomous UAV's performance as the environment's randomness increased. Overall, we aimed to create an environment that simulates the challenges faced by autonomous UAVs in construction sites, while also allowing us to control variables such as the movement of workers and the layout of obstacles.

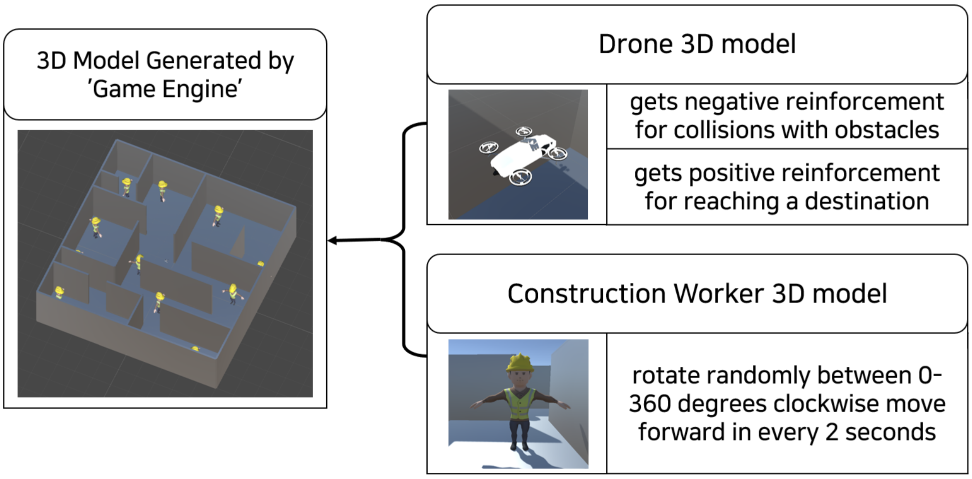

Fig. 2. Learning environment

We place UAVs in this environment for training and testing it's traveling performance. The environment is characterized by walls and a floor, which are labelled as obstacles. Additionally, there are eleven workers in the environment, each of which is labelled as a destination where RL agent can interact with. A RL agent gets negative reinforcement (-3) for collisions with obstacles, positive reinforcement (+5) for reaching a destination, and other reinforcement based on the UAV's distance from the target worker. Then the RL agent is trained to increase its total reward by avoiding collisions with obstacles, getting closer to the target worker, and sequentially reaching all destinations with optimal path. If the UAV collides with an obstacle, it receives negative reinforcement, and the episode is reset. When all destinations are reached, the total reward is calculated, and if it reaches 55, the episode ends, and the system is restarted.

To evaluate the system, the UAV is flown in the same environment, and the time taken to reach all destinations is measured. Additionally, the time taken for the UAV using GPS navigation (GNU) to complete the same task is measured for comparison. To test the system's adaptability and responsiveness to randomness, three different environmental variables are implemented, including different worker speeds and rotation intervals. 1) Enter the worker's movement speed as 2, rotate the direction of progress every 2 seconds, 2) enter the worker's movement speed as 4, rotate the direction of progress every 2 seconds, 3) enter the worker's movement speed as 8, and rotate the direction of progress every 0.5 seconds.

Overall, the autonomous UAV system using reinforcement learning is successfully implemented and tested in various environments. It demonstrates its adaptability and effectiveness in navigating complex environments. The system's reinforcement learning algorithm allows it to learn from its mistakes and adjust its behavior accordingly, resulting in improved performance over time. This system could be used in a variety of applications, such as warehouse inventory management, search and rescue operations, and precision agriculture.

4.2. Results

The following presents the driving results of an autonomous UAV using reinforcement learning (RNU) and a GPS navigation UAV(GAU) based on different variables.

Table 1. Driving result in Speed = 2, Rotate once every 2 seconds

	Case 1) Speed = 2, Rotate once every 2 seconds		Case 2) Speed = 4, Rotate once every 2 seconds		Case 3) Speed = 8, Rotate once every 0.5 seconds	
	with RLU	with GAU	with RLU	with GAU	with RLU	with GAU
1st	1m 21s	1m 29s	29s	1m 12s	38s	1m 44s
2nd	1m 16s	1m 25s	41s	1m 18s	44s	1m 8s
3rd	1m 18s	1m 34s	42s	45s	35s	1m 18s
4th	2m 37s	1m 21s	51s	1m3s	29s	1m 23s
5th	1m 26s	1m 54s	47s	58s	53s	1m 12s
6th	1m 40s	1m 26s	32s	1m6s	29s	1m 27s
7th	1m 7s	1m 19s	38s	1m 1s	40s	1m 16s
8th	1m 16s	1m 29s	35s	52s	47s	1m 31s
9th	1m 11s	1m 33s	47s	1m 16s	36s	1m 27s
10th	1m 8s	1m 37s	39s	1m 5s	44s	1m 29s
Min value	1m 26s	1m 30.7s	40.5s	1m 3.6s	39.5s	1m 24.5s

Table 1 shows the results of ten trials of autonomous UAV navigation using both RLU, GNU in an environment where the worker's movement speed was set to 2 and the direction changed every two seconds. Despite a slight difference of 4.7 seconds, the RLU demonstrated shorter navigation times compared to the GNU. And second case presents the results of ten trials of autonomous UAV navigation in an environment where the worker's movement speed was set to 4 m/s and the direction changed every two seconds. The navigation time of the RLU was significantly shorter, with an average of 40.5 seconds per trial compared to the GNU, which required an average of 1 minute and 3.6 seconds per trial. This is a substantial difference of 23.1 seconds.

In a third case, ten trials of autonomous UAV navigation were conducted in an environment where the worker's movement speed was set to 8 m/s, and the direction changed every 0.5 seconds. Similar to the previous trials, the RLU showed a considerable advantage, with an average navigation time of 39.5 seconds per trial compared to the GNU, which required an average of 1 minute and 24.5 seconds per trial, representing a substantial difference of almost double the time.

5. Discussion & Limitations

This study can be seen as an approach to developing autonomous UAVs for complete unmanned construction sites. Based on our previous experiment results, we have confirmed that reinforcement learning algorithms can be effectively applied to construction sites with uncertainty and randomness. We proposed a system that uses LiDAR sensors for object detection to train autonomous driving algorithms without providing any separate information such as obstacle locations or target points. Through this, we provided solutions to problems previously raised for applying UAVs to work monitoring on construction sites, such as pre-determined paths and incomplete autonomous driving. This enables complete unmanned work monitoring at construction sites by placing only one fully autonomous UAV on-site, instead of relying on workers or managers to take photos or videos to check the progress of work through CCTV cameras on-site.

In this study, we only conducted experiments in a virtual environment within the Unity game engine. This means that it was conducted only in a simulation without any variables such as unexpected problems in a natural environment (e.g., undetected obstacles, strong winds affecting UAV driving, and objects moving too fast to detect). Therefore, there is a need for research to apply our autonomous driving algorithm to actual UAVs and fly them in real construction sites environments. For this, we need to use ubuntu ROS and Gazebo to enable autonomous driving commands to be sent to actual UAV modules.

Also, the movement of our virtual UAV in the simulation environment was in two dimensions, not in three dimensions. It consisted of very simple movements such as rotation and forward/backward motion, which are highly simplified compared to the actual UAV's ability to move in 3D and 360 degrees. In addition, the UAV's target is limited to simply finding and reaching the detected target using LiDAR sensors without collision. In actual UAV use for construction sites progress monitoring, various tasks are required such as reaching the target location and continuously capturing images, tracking target workers, etc. Therefore, it is necessary to instruct the UAV to perform more complex behaviors and enable autonomous driving for such behaviors.

In summary, the virtual UAV we created in this study has limitations compared to actual UAV usage. Therefore, further research is needed to enable actual UAVs to perform more complex behaviors and autonomous driving in real construction sites environments.

6. Conclusion

This study presents the development method and performance verification of an autonomous UAV for monitoring construction work using reinforcement learning algorithms. By increasing the degree of random movement of obstacles, the autonomous UAV was able to achieve faster target approach and capture while avoiding obstacles more effectively. This research can be seen as an approach to the complete automation of construction sites monitoring through autonomous UAV development, and it is expected to have a positive impact on the complete automation of work monitoring in construction sites.

References

[1] F. Giones and A. Brem, “From toys to tools: The co-evolution of technological and entrepreneurial developments in the drone industry,” Business Horizons, vol. 60, no. 6, pp. 875–884, Nov. 2017, doi: 10.1016/j.bushor.2017.08.001.
[2] Drone Market Report 2020–2025; Technical Report; Drone Industry Insight: 2020.
[3] J. H. Lee, J.-H. Park, and B.-T. Jang, “Design of Robot based Work Progress Monitoring System for the Building Construction Site,” 2018 International Conference on Information and Communication Technology Convergence (ICTC), Oct. 2018, doi: 10.1109/ictc.2018.8539444.
[4] Kim, Taehoon.(2021).Construction Site Monitoring using Vision Artificial Intelligence.Review of Architecture and Building Science,65(12),64-67.
[5] D. Kim, M. Liu, S. Lee, and V. R. Kamat, “Remote proximity monitoring between mobile construction resources using camera-mounted UAVs,” Automation in Construction, vol. 99, pp. 168–182, Mar. 2019, doi: 10.1016/j.autcon.2018.12.014.
[6] J. Youn, “Design and Implementation of UAV Based Construction Site Monitoring and Analysis System,” Journal of the Korea Academia-Industrial cooperation Society, vol. 22, no. 12, pp. 116–123, Dec. 2021, doi: 10.5762/kais.2021.22.12.116.
[7] K. K. Han, D. Cline, and M. Golparvar-Fard, “Formalized knowledge of construction sequencing for visual monitoring of work-in-progress via incomplete point clouds and low-LoD 4D BIMs,” Advanced Engineering Informatics, vol. 29, no. 4, pp. 889–901, Oct. 2015, doi: 10.1016/j.aei.2015.10.006.
[8] Hitech (2019) “Point Cloud to BIM”, https://www. hitechcaddservices.com/bim/support/point-cloud-to-bim/
[9] Moeini, S., Oudjehane, A., Baker, T., & Hawkins, W. (2017). Application of an interrelated UAS–BIM system for construction progress monitoring, inspection and project management. PM World J. VI (VIII), 1-13
[10] SPAR3D (2016), “How Drone Videos and Augmented Reality can Help monitor Construction Projects”https://www.spar3d. com/blogs/guest-blog/monitor-construction-with-ar-fromdrone-videos/
[11] Anwar, Naveed, Muhammad Amir Izhar, and Fawad Ahmed Najam. "Construction monitoring and reporting using drones and unmanned aerial vehicles (UAVs)." The Tenth International Conference on Construction in the 21st Century (CITC-10). 2018.
[12] S. Kim and J. Irizarry, “Framework for Human Performance Analysis in Unmanned Aircraft System (UAS) Operations in Dynamic Construction Environment,” Construction Research Congress 2018, Mar. 2018, doi: 10.1061/9780784481264.004.

[13] S. Russell and P. Norvig, “A modern, agent-oriented approach to introductory artificial intelligence,” ACM SIGART Bulletin, vol. 6, no. 2, pp. 24–26, Apr. 1995, doi: 10.1145/201977.201989.
[14] Minjae Yoo, Soyi Jung, Joongheon Kim.(2022).A Study on the autonomous driving technology and simulator using deep reinforcement learning.Proceedings of Symposium of the Korean Institute of communications and Information Sciences,(),1486-1487.
[15] S. Y. Jang. et al. (2019). Research trends on deep reinforcement learning. Electronics and Telecommunications Trends, 34(4), 1-14. DOI : 10.22648/ETRI.2019.J.340401
[16] W. I. Shim, T. H. Park & K. J. Kim. (2018). Comparison of policy optimization reinforcement learning for simulated autonomous car environment. Proceedings of the Korean Society of Information Sciences , 833-835.
[17] W.-J. Jung, “Build reinforcement learning AI process for cooperative play with users,” Journal of Korea Game Society, vol. 20, no. 1, pp. 57–66, Feb. 2020, doi: 10.7583/jkgs.2020.20.1.57.

DESIGN TRACKING: TRACK AND REPLAY BIM-BASED DESIGN PROCESS

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Abstract

Among different phases of the life cycle of a building or facility, design is of the utmost importance to ensure safety, efficiency and sustainability of the building or facility. How to control and improve design quality and efficiency has been explored for years, and more studies emerged with the popularization of Building Information Modelling (BIM). However, most of them focused on the extraction of design behaviors, while paying less attention to how a design is formed. Therefore, this study proposes an approach to tracking and replaying the BIM-based design process by integrating data logging and 4D visualization techniques. First of all, potential design behaviors and procedures are analyzed and extracted by observing how a designer designs a BIM model. Meanwhile, the required data for logging design process is defined and a relevant method to collect these data is developed based on the APIs of BIM software. Then, strategies on how to visualize different design procedures are designed and implemented via 4D visualization. Finally, a prototype system is developed based on Autodesk Revit and validated through a case study. Result shows that the proposed approach enables intuitively and interactively review of the design process, and makes it easier to understand design behaviors and even identify potential pitfalls, thus improving the design efficiency and quality.

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Keywords: building information modelling, design process tracking, design behavior, 4D visualization.

1. Introduction

In the life cycle of engineering construction projects, the three core stages are the design stage, the construction stage and the operation and maintenance stage. The design stage often only takes up a small part of the time and cost of the whole project, but it plays a decisive role in the cost, quality and duration of the project [1]. Therefore, improving the efficiency and quality of the design stage is very important to ensure the success of the whole project. In order to study the specific methods to improve efficiency and quality of the design stage, it is necessary to conduct a detailed analysis of the specific process of design. The design process is of significant importance because it can reflect factors directly related to design efficiency and quality, such as the designer's ideas, behavioural habits and experience level. This information usually cannot be obtained from the design results, such as blueprints, drawings, calculation results.

Nowadays, BIM-based design has become more and more common in the architecture, engineering and construction (AEC) industry. Building Information Modelling (BIM) provides a data integration platform for the whole life cycle of buildings, recording comprehensive and diverse data. The traditional CAD-based design can only provide design results, while BIM-based design can record the detailed data of the design stage and provide valuable information for studies on the specific process of design. There have been some studies focusing on tracking the specific process of design. Yarmohammadi, etc. [2] evaluated the modelling efficiency of different designers by analysing the real-time recorded design process data, and based on this, gave a staffing plan to optimize the efficiency of the whole design team. Based on the design process information mined from the BIM log file, Pan, etc. [3] established a prediction model for design behaviour using Long Short-Term Memory neural network.

However, these studies based on data analysis had the following shortcomings. First of all, most of the studies extracted the design behaviour data from BIM software and analysed the data outside it. This process can be time-consuming, and the use of multiple data analysis software also makes the whole process very complicated. Secondly, it also took time to send feedback on the conclusion to the designers after the data analysis. The feedback including data results (data, tables, text conclusions, etc.) can be abstract so that designers cannot quickly identify and understand the specific modelling details. This makes it more difficult to match the specific design behaviour with the feedback to draw any practical conclusion [4].

To address this problem, we can use visualization technique to show the design process to the designers which provides designers with a quick way to learn and summarize experience, and the researchers with a means to observe the design process visually. In the AEC industry, especially in the studies related to construction planning, the 4D visualization technique has been used to combine the 3D data of BIM models with the schedule information to obtain the 4D analysis model of the building life cycle, so as to visually display the project progress and assist in checking the correctness and constructability of the building design [5]. There are many specific implementation schemes of 4D visualization technique [6], but most of them need to use additional software and link the BIM model with it. However, the data conversion between different kinds of software involves steps such as the unification of format and type, and the process is complicated [5].

To address the shortcomings of the previous studies, this paper designed a system for tracking and intuitively "replaying" the design process based on 4D visualization technique, which can realize the 4D visualization of the modelling process directly in the BIM software used by designers. The system can meet the requirements of quickly and accurately locating the specific design process and analysing the design behaviour characteristics. This process can transform the implicit knowledge hidden in design behaviour into explicit knowledge expressed through written experiences, providing clear suggestions and guidance for future design work [7]. This study first analysed the design behaviour of designers based on the theory of Human-Computer Interaction and summarized the data requirements of the system. This analysis not only gave corresponding data requirements, but also provided a foundation for designing specific 4D visualization strategy. Specific algorithms were then developed to collect data and realize visual effects. To prove the effectiveness of the proposed system, a prototype system based on Revit software was developed. Finally, a case study using the prototype was conducted to validate the proposed system. In the end, this paper discusses the value of the system and the deficiencies that need to be further improved.

2. Methodology

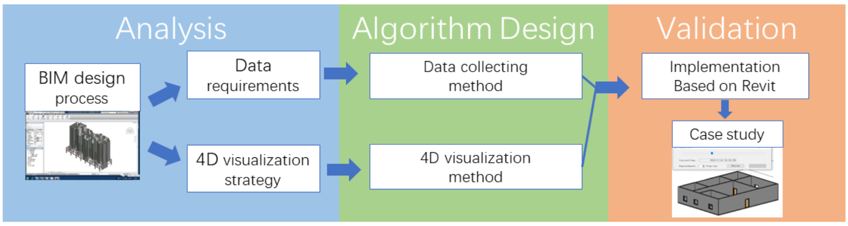


Fig. 1. Methodology of this study

As shown in Fig. 1, this study first analyses the BIM design process to summarize the data requirements of the system and give a clear goal for visualization. The specific method of 4D visualization is the core part of this system, therefore it is crucial to analyse and propose an implementation strategy of 4D visualization for specific issues of concern in this study. Specifically, this study proposed a 4D visualization strategy combining visual effects and interactive UI window. The algorithm design stage produces a data collecting method to address the data requirements and a specific method to realize 4D visualization in BIM software. Finally, this study implemented specific code based on Autodesk Revit software to verify the effectiveness of the design, and tested it with a case study in a specific BIM model.

2.1. Analysis of BIM Design Process and Data Requirements

The design process based on BIM is a human-computer interaction process. In this process, information flows in two directions. The designer inputs instructions through the computer input hardware, the computer then processes these instructions, makes modifications to the model, and returns the new model to the designer through the screen. The designer can then carry out the next modelling step according to the current results. Just like replaying a video, this system should enable users to see when each step was carried out on the timeline in order to meet the requirements of the basic replay function. The most important operations that make changes to the BIM model can be divided into three categories: creation, modification and deletion [8]. These are also the three types of user operations that this study focuses on and require visualization.

The core data requirement of tracking and replaying modelling process is the time series data of BIM model modifications. These time series data should contain two types of information. First of all, data that can uniquely identify model elements is required, which is usually the ID of elements in the model. The second type is the information about user operations, including the type of operation (creation, modification, deletion, etc.), the time of operation and other extra data that may be required.

Table 1. Data requirements of different types of operations

Types of operation	Common data requirements	Different extra data requirements
Creation	IDs, Time	--
Modification		Specific change data. e.g., spatial position change, material change
Deletion		Data needed to reconstruct the element

Different types of operation need different extra data (Table 1) and the complexity of the required data varies greatly. For example, the creation operation requires no extra data, while the deletion operation needs all the parameter information needed to recreate the deleted element. This is because if we want to visualize an element that has been deleted from the database, we first need to be able to reconstruct it in the model. However, the quantity and fineness of the required data are not absolute and can be adjusted according to user’s demands. If it is only needed to replay the process of creation elements, or to be only accurate about the basic information of the deleted elements, such as the geometric position and size of the deleted element, it is possible to reduce the number and fineness of corresponding data requirements to simplify the data collecting process.

2.2. Analysis of 4D Visualization Strategy

This study only relies on BIM software for visualization, its advantage is convenience and speed, but it is also subject to mainly two aspects of limitations. Firstly, BIM software can only provide limited visual effects-related settings for visualization, and most BIM software does not allow deeper customization for graphic renderers. Secondly, additional windows need to be developed to control the visualization process and serve as data panels. Therefore, the strategy that BIM based 4D visualization should adopt is to use the visual effects provided by the software combined with interactive windows that control visualization and display relevant data.

The visual effect of "replay" can be realized through the display mode or display style of elements in BIM software. The display mode is mainly related to the current state parameter of the element, such as whether it is selected, whether it is in the hidden state, etc. BIM software uses different visual methods to highlight components in these different states, which can be used by our visualization purpose. For example, in Revit, an element is shown in blue if selected. The display style depends on the rendering options provided by the graphic renderer. For example, Revit provides display style options such as "Realistic", "Wireframe", and "Consistent Colours". These options only affect the display effect of the elements in a particular view, and do not change actual parameters of them.

The window providing interactive functions needs to control the progress of 4D visualization and dynamically adjusts the visual effects of elements in the view according to user operations. We also need windows to display some relevant information, such as the time of the current operation, the types of the elements involved and the type of operations. If the demand for data display is low, these two kinds of windows can be merged together.

2.3. Data Collecting Method Design

In this study, real-time data collecting method was used. Real-time data collecting can be carried out through software plugins of BIM software, which can be developed based on redeveloping method. The cost of additional software development is high and it is difficult to obtain the data in the BIM model, so the plugin based on redevelopment is more suitable. Most sorts of BIM software on the market have open Application Programming Interfaces (APIs), which usually provide rich functions for redevelopment.

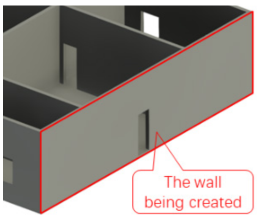
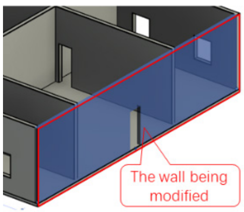
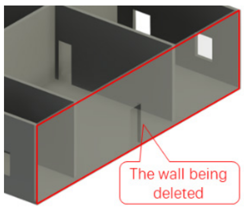
The data requirements of this study include the user's operation data, and the collection of this part of data needs to be realized with the help of the *Event* system. Generally, plugins need to subscribe to events related to model modification and element change provided by BIM software to obtain relevant data when these events occur. The collected data needs to be exported and stored in a serialized way, and different data belonging to different models should be stored separately.

2.4. 4D Visualization Method Design

The 4D visualization strategy obtained from the previous analysis is a universal principle that can be applied to almost all kinds of BIM software. However, for each specific BIM design software, the functions and rendering parameters provided by the software are different, so the 4D visualization method in each specific software needs to be designed independently. This section provides a possible visualization scheme for Autodesk Revit.

The specific plan for visual effects of 4D visualization is shown in the table 2. Different design behaviours are presented in different ways by visual effects. A replay control window is needed to read the data files and modify the BIM model in real-time based on user actions to achieve visual effects. This window should also present relevant data.

Table 2. A possible visualization plan for Revit

Types of operation	Creation	Modification	Deletion
Visual effect	Hide/display mode set to display	Shown in blue	Set to be transparent
Examples			

2.5. Implementation and Validation

Specific implementations and case studies are important ways to test the usability and effectiveness of a newly proposed system. This study takes Autodesk Revit software as an example to develop specific codes, collect required design process related data through the Revit plugin, and provide modelling process replay functionality. Considering the difficulty of development, the plugin developed in this study only implements replay of creation operations. The developed plugin will be used on a simple specific BIM model for specific case testing and analysis. The results of the case study are then used to evaluate the functionality, efficiency, and user experience of the plugin.

3. Implementation and Case Study

3.1. Implementation

This study developed a prototype system based on Revit to realize the basic tracking and replaying functions for BIM-based design, and verified the feasibility and effectiveness of the proposed system. The main body of the prototype system is a plugin developed for Revit 2023 on Windows.

Tracking the creation of an element requires the identification data of the element and the time of the creation operation. In Revit software, each element of an independent model file has a unique *Elementid* attribute as the identification code. This attribute can be easily obtained using APIs, and the time information can be obtained directly through the *System.DateTime* method provided by Windows. For real-time recording, the system subscribed to two events provided by Revit, *DocumentOpenedEvent* and *DocumentChangedEvent*. The former notifies the plugin after opening a model file. At this time, the plugin retrieves whether there is a data record file corresponding to the model file. If not, it creates a data recording file and prepares the file stream for subsequent writing. If there is a matching data record file, it opens the file and prepare the file stream. The latter event will notify the plugin after the model changes, and will provide a list of *ElementId* of all newly added elements. The plugin then integrates these data together with the time information into a structured string and stores it in the data file.

The data recording file of the prototype system adopts the txt format, mainly considering that the data to be recorded during the modification and deletion operations is relatively complex. This may cause the length and complexity of the records to vary greatly, so a certain degree of structure is sacrificed to ensure flexibility and versatility which may benefit further development.

The “replay” visual effect is achieved by changing the hide/display mode of elements. For a specific point in time, elements that have been created are displayed, and elements that have not yet been created are hidden. Over time, hidden elements change to the displayed state one by one in the time order of creation. In Revit, the hide and display of elements are set by the viewport (*View*). The hide/display of elements are designated by a specific *View*. In other word, if an element is hidden in one *View*, it is still displayed in other *Views*.

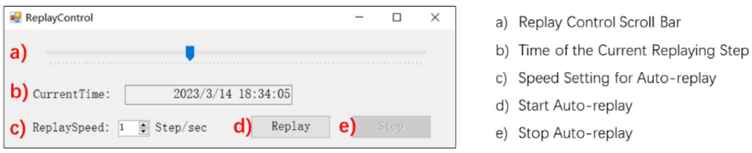


Fig. 2. Replay control interface

To provide users with more control options over the replay function, the plugin includes a dialog interface (Fig. 2). Clicking the corresponding button on the ribbon menu opens the replay control interface and all elements are set to be hidden to take the user back to the starting point of modelling. All playable steps are distributed evenly on the scroll bar (a) in time order. The scroll bar is both a timeline and a “video progress bar”. Users can drag the handle at will and observe the changes of the model. The time of the handle position is displayed in the textbox (b). Users can also let the plugin play automatically by setting the playback speed (c) and press *Replay* (d). It will play the set number of steps every second. Automatic replay can be stopped by pressing *Stop* (e) at any time, and it will also stop automatically at the end of the replay progress. When you close the interface, the hide/display state of all elements in the view will remain. If you need to restore all the elements of the model to the display state, you need to drag the scroll bar to the end and then close the interface.

3.2. Case Study

This study takes a simple BIM model as an example to verify the effectiveness of the prototype system. The model has two floors, including common components such as walls, slabs, roof, doors, windows, stairs. Figure 3 shows three moments in the actual replay process and the complete model.

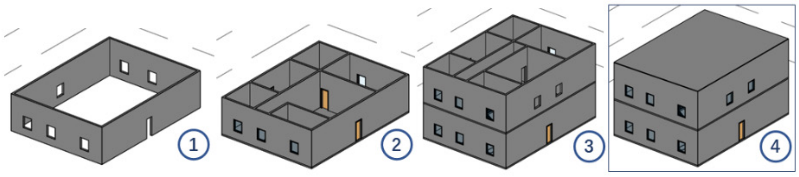


Fig. 3. Three moments in the replay process and the complete model

The test proves that the plugin can realize the playback function well and give users sufficient control over the replay function. During the replay, designers can review their operations and summarize experience to improve design efficiency. For example, most elements on the second floor of the case model can be created quickly by copying elements from the ground floor. If designers discovered that they had been creating elements one by one, they can summarize experience and adopt more efficient methods in future modelling tasks.

4. Conclusion

Current BIM-based design process data analysis is not intuitive and the existing visualization scheme is complex. This study proposes a tracking and playback system for design behaviour to address these problems. The system collects the user's design process data in real time and intuitively displays the design process in BIM software. The system provides interactive control over the replay process and basic information about the current replay progress. The effectiveness of the system is verified by the development of a prototype system based on Revit and a case study on a simple BIM model. Designers can review their design process step by step and discover which specific operations can be optimized for better efficiency and equality. The recorded data file can also provide basic data for future research, and the plugin can also be improved to record more types of data such as mouse movement, keyboard input and executed commands.

The system still has two deficiencies. Firstly, the real-time data collection method poses a problem. For models that have been partially completed elsewhere, the plugin can only replay the modelling process after using the plugin. In future research, data sources can be supplemented through log files and other means. Another disadvantage is that the current system only focuses on the creation, editing and deletion of elements, while there are many other design behaviours worthy of attention, such as perspective change, command input, etc. More diverse and detailed information of user operations should be included in future studies.

Acknowledgements

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References

[1] V. Moayeri, O. Moselhi, and Z. Zhu, “BIM-based model for quantifying the design change time ripple effect,” *Can. J. Civ. Eng.*, vol. 44, no. 8, pp. 626–642, Aug. 2017, doi: 10.1139/cjce-2016-0413.
[2] S. Yarmohammadi and D. Castro-Lacouture, “Automated performance measurement for 3D building modeling decisions,” *Automation in Construction*, vol. 93, pp. 91–111, Sep. 2018, doi: 10.1016/j.autcon.2018.05.011.
[3] Y. Pan and L. Zhang, “BIM log mining: Learning and predicting design commands,” *Automation in Construction*, vol. 112, p. 103107, Apr. 2020, doi: 10.1016/j.autcon.2020.103107.
[4] T. Nakamura and T. Igarashi, “An application-independent system for visualizing user operation history,” in *Proceedings of the 21st annual ACM symposium on User interface software and technology*, New York, NY, USA, Oct. 2008, pp. 23–32. doi: 10.1145/1449715.1449721.
[5] S. Staub-French, A. Russell, and N. Tran, “Linear Scheduling and 4D Visualization,” *Journal of Computing in Civil Engineering*, vol. 22, no. 3, pp. 192–205, May 2008, doi: 10.1061/(ASCE)0887-3801(2008)22:3(192).
[6] P. Ivson, D. Nascimento, W. Celes, and S. D. Barbosa, “CasCADe: A Novel 4D Visualization System for Virtual Construction Planning,” *IEEE Transactions on Visualization and Computer Graphics*, vol. 24, no. 1, pp. 687–697, Jan. 2018, doi: 10.1109/TVCG.2017.2745105.
[7] Z.-Z. Hu, S. Leng, J.-R. Lin, S.-W. Li, and Y.-Q. Xiao, “Knowledge extraction and discovery based on BIM: a critical review and future directions,” Archives of Computational Methods in Engineering, Apr. 2021, doi: 10.1007/s11831-021-09576-9.
[8] J.-R. Lin and Y.-C. Zhou, “Semantic classification and hash code accelerated detection of design changes in BIM models,” *Automation in Construction*, vol. 115, p. 103212, Jul. 2020, doi: 10.1016/j.autcon.2020.103212.

DEVELOPING A DIGITAL TWIN ON A UNIVERSITY CAMPUS TO SUPPORT EFFICIENT AND SUSTAINABLE BUILDINGS

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Abstract

This study presents a case study for the proof of concept of developing and integrating a digital twin for an open floor-plan office space in a university campus to assess the (near) real-time monitoring of different elements, including temperature, humidity and occupancy. The system uses various weather sensors and a camera feed as input to a computer vision algorithm to detect (near) real-time occupancy. The goal is to use this platform to provide real-time information about ambient and occupancy information that users and facility managers can use to make buildings more efficient and sustainable by considering users' involvement and feedback.

Peer-review under the responsibility of the scientific committee of the Creative Construction Conference 2023.

Keywords: Blueprint, Game Engine Technology, Industry 5.0, Internet of Things, undergraduate research, Unreal Engine.

1. Introduction

Digital twins and Industry 5.0 aim to optimize manufacturing processes by leveraging cutting-edge technology. Industry 5.0 is the next phase in the industrial evolution and emphasizes collaboration between humans and machines, while digital twins are virtual representations of physical assets or processes, and they can be used to simulate, analyze and optimize the performance of a building throughout its lifecycle [1]. For example, with a digital twin, it is possible to optimize the design and operation of a building to reduce energy consumption, improve indoor air quality, and minimize waste [2]. Digital twins can be used to optimize energy usage, reduce waste, and minimize the environmental impact of manufacturing processes. Industry 5.0 aims to create more sustainable and eco-friendly production processes by leveraging advanced technologies like artificial intelligence and the Internet of Things (IoT). Additionally, digital twins can be used to simulate and analyze the impact of different scenarios, such as changes in weather or occupancy patterns, to identify potential issues and opportunities for improvement [3]. A digital twin can be developed on different platforms. One approach is using game engine technology to provide realistic digital environments. In construction research and related applications, game engines are becoming popular. For example, game engines have been used to create interactive training tools for construction safety applications using various technologies such as VR and AR [4]–[15]. Other applications include Interactive Building Information Anatomy Modeling to allow users to dive into the BIM model using VR and retrieve information about building components, such as material information [16] or the development of a workspace management framework integrating the work planning phase with spatial analysis [17]–[19].

One of the key synergies between digital twins and Industry 5.0 is the ability to create more efficient and effective manufacturing processes. Digital twins can simulate production lines, test new designs, and optimize operations at a relatively low cost. This allows manufacturers to identify potential issues before they occur, reduce downtime, and improve product quality. Industry 5.0 emphasizes the collaboration between humans and machines, and digital twins can support this collaboration by providing workers with real-time data and insights that help them make better decisions [20].

With this background, this study presents a proof of concept for developing and integrating a digital twin in a university campus. This allows to gather information and assess in (near) real-time different elements, including temperature, humidity and occupancy, beyond traditional building management systems. This project created a favorable ecosystem that allowed the involved undergraduate students to get hands-on experience developing the components needed, from sensors to model development and connection between the digital and physical environments. This study was also done in collaboration with the industry to support the students and assist with creating the digital model using game engine technology. The ultimate goal was to create a proof-of-concept platform that allows users and facility managers to visualize (near) real-time information about different components of the space they are in and, ultimately, to make buildings more efficient and sustainable.

2. Literature review

Building Information Modeling (BIM) has changed how information can be generated, stored, and exchanged among various stakeholders in the construction industry. However, digital technologies are fast evolving and integrated with many phases of construction projects. Therefore, BIM should be considered in conjunction with these emerging technologies. Sacks et al. [21] indicate that digital twin models, Automated Project Performance Control (APPC), Construction 4.0, and automated data acquisition technologies remain emerging research areas in the AEC industry.

Although the term “Digital Twin” was first attributed to NASA [22], the concept and model of the digital twin were introduced in 2002 by Grieves [23]. He proposed the digital twin as the conceptual model underlying product lifecycle management (PLM) [24]. Different industries have used digital twins for a while for different applications. For example, the aviation industry has been using twin models of aircraft and airports. The manufacturing industry uses digital twins for small components and large factories. These digital twin models are also used for safety and logistics maintenance to maximize the efficiency of the products [25]. Car manufacturers use this technology to analyze the performance of vehicles before production begins [26].

Implementing digital twins requires careful planning and execution to realize the potential benefits of this technology. One of the common concerns for implementing digital twins is the management of data and physical sensors from a wide range of applications. For instance, some urban planning applications require data collection from waterways, air, and soil, which must be managed and centralized for proper use. Some barriers include misalignment of data interpretation which can hinder the future implementation of digital twins. The inputs, outputs, and feedback vary depending on how digital twins are implemented and ultimately used. For example, for whom it is intended (citizens, public administrators, etc.), during which phase (or phases) it is implemented (planning, construction, O&M), and what type of IoT sensors and data are required (noise pollution, air quality, energy, occupancy etc.) need to be well defined and clearly identified at an early stage. To assist with that, Zhao et al. [27] developed a bottom-up framework to ease the implementation of digital twins to support facility managers during the O&M of buildings. They provided an aggregate landscape of DT applications to manage facilities and a conceptual framework for stakeholders concerned with their FM decision-making processes.

The use of digital twins varies across different sectors and spans different disciplines. For instance, Scientists from the National Oceanic and Atmospheric Administration (NOAA) and the National Climatic Data Center (NCDC) use historical rainfall data from digital twins to virtually test the operation of existing stormwater systems. This addresses outdated stormwater systems buckling under the stress of heavier rainfall and increased flooding caused by climate change [28]. As part of the renovation of the UK rail infrastructure, researchers from Cambridge Centre for Smart Infrastructure and Construction (CSIC) developed a digital twin platform to gather real-time data to provide useful information to support engineers and asset managers to schedule safer and proactive maintenance plans [29],[30].

In 2021, the New York State Department of Transportation (NYSDOT) used digital twins to assess and replace the East 138th Street bridge in New York City’s Bronx borough. Completing the project in such a congested area involved complicated structural design and coordination using a digital twin as the primary construction document. The digital twin may now be continuously updated and used as a tool for asset management and bridge inspection [31].

Bortoloni et al. [3] reviewed applications of digital twins in the field of energy efficiency for buildings. They identified 32 articles (from 2019 to 2022). From the review of those articles, they classified them into four topics related to applications of digital twins (1-Design optimization; 2-Occupants' comfort; 3-Building operation and maintenance; and 4-Energy consumption simulation). They concluded that based on the small number of publications found and how recent they were, the use of digital twins in the field of buildings energy efficiency is still in its infancy.

A few studies highlight the potential of digital twins to improve sustainability in the built environment by optimizing building performance, reducing waste and energy consumption, and improving resource utilization. They also suggest that digital twins have the potential to play an important role in the design, construction, and operation of efficient and sustainable buildings and infrastructure systems.

3. Case study

The case study presented in this article extends the preliminary work conducted for the high-level integration of a digital twin at a university campus. For that project, the Blender GIS addon [32] was used to select the area of interest and generate the 3D context in a quick and accurate manner. After that, the 3D model was exported from Blender in fbx. format and imported into Unreal Engine as the platform to model the 3D environment.

The high-level integration of the digital twin consisted of outdoor weather and environmental data obtained from https://api.openweathermap.org and some of the sensors deployed and maintained by the Center for Interacting Urban Networks (CITIES) as part of their CITIESair project [33]. The obtained data included the outside temperature of the area, humidity, pollutant levels (SO2, CO2, PM, etc.), the sun's position, and the level of visibility or amount of dust in the weather. Only real data for indoor pollutant levels was available in one building (shown as green in Figure 1). For the rest, dummy data was generated to show proof-of-concept functionality but could be easily replaced with real data once the required sensors are in place. After obtaining these values in real-time, Unreal Engine actors were used to visualize each of these aspects (updated according to the real-time change in these values). For example, the *Volumetric Cloud* actor in the model changes the intensity of the clouds based on the real-time cloud intensity values obtained from the API. With that information, the *Set Tracing Max Distance* function in Blueprints modifies the intensity of the clouds to show a clear or cloudy sky in the game engine platform. An example of the visualization in the game engine platform of that work displaying a mix of actual and generated data for Fine Particles (PM 2.5) is shown in Figure 1. The building in green has data from an actual sensor installed. The rest of the buildings have dummy data for display purposes only. Information in the upper portion of Figure 1 (e.g., Temp, cloud conditions, humidity, wind speed and direction) is real data from the OpenWeather API at the time of the visualization.

Figure 1: General view of the visualization of different elements considered during the preliminary work for the high-level integration of a digital twin at a university campus.

To expand the previous work, the rest of the study considers a more detailed space (interior of a building) consisting of an open floor-plan office space on a university campus to assess the (near) real-time monitoring of different elements, including temperature, humidity and occupancy, as a proof of concept for developing a digital twin. The process followed for the development of the digital twin involves different steps. The general process for this study is shown in Figure 2.

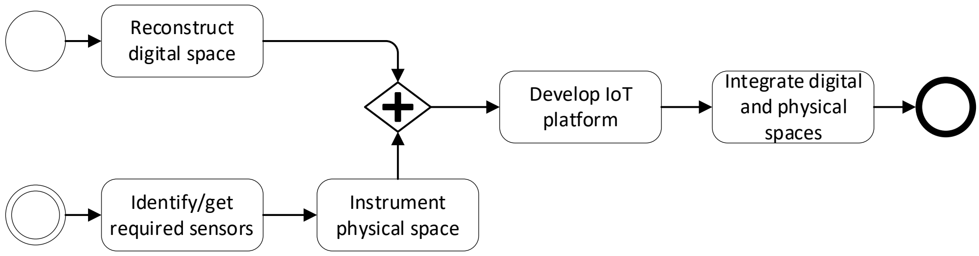


Figure 2: Main steps for the development of the digital twin model for this study

First, it entails reconstructing the digital space (assuming one does not exist already), creating a virtual representation that mirrors the physical environment. Next, real-time data acquisition takes place, capturing information from physical space. This data is then streamed to an Internet of Things (IoT) platform for further processing and analysis. Finally, data streaming is integrated with the digital space, connecting specific elements that are influenced by the (near) real-time data sourced from the physical environment.

3.1. Digital space reconstruction

The space used for this study consists of an open-floor plan office space on a university campus with a total area of approximately 195 m^2 hosting CITIES. Due to the lack of an as-built digital model (e.g., 3D CAD files or BIM) of that space, different tools were evaluated to generate the 3D environment for the digital model. Different instruments were employed to assess their applicability to this case (Table 1). In particular, we utilized three unique types of laser scanning technologies. The Faro Focus laser scanner was primarily used to collect most of the geometric and color data. Nine individual scans were carried out at a consistent height of 1.2 m and four additional scans at a lower height of 0.7 m to accurately depict the area beneath the furniture. A solitary scan at a height of 1.6 m was also performed to encompass the upper sections of tables and shelves.

The Hovermap laser scanner, with its mobile nature, offers a significant advantage over its stationary counterparts like Faro and Leica, as it is capable of scanning areas that are otherwise hidden, thereby reducing occlusion. However, the proficiency of the Hovermap laser scanner mainly lies in scanning geometry, with its ability to capture color data being somewhat limited. Hence, we confined ourselves to using only its positional data.

Ultimately, the Leica scanner was employed to conduct further scans and ensure thorough coverage of the area of interest under various lighting conditions.

Table 1. Main characteristics of the equipment used for reality capture of the space in this study

Equipment	Field of view	3D point accuracy	Range	Point measurement rate	Source
Leica BLK360	360° (horizontal) / 300° (vertical)	± 6mm @ 10m / ± 8mm @ 20m	0.6 - 60 m	Up to 0.36 million points/sec	[34]
Faro Focus S 350 Plus	360° (horizontal) / 300° (vertical)	± 2mm @ 10m / ± 3.5mm @ 25m	0.6 - 350 m	Up to 2 million points/sec	[35]
Emesent Hovermap ST	360° (horizontal) / 290° (vertical) (but moveable)	± 20 mm in general environments ± 15 mm in typical indoor and underground environments ± 5 mm isolated change detection capability	0.4 - 300 m	Single Return Mode: up to 0.3 million points/sec Dual Return Mode: up to 0.6 points/sec	[36]

Different sensors were developed, tested, integrated into the physical space, and linked to the digital model. The digital twin environment was developed in Unreal Engine 4.27 from Epic Games [37]. To test the quality of the point clouds in Unreal Engine, the Lidar Point Clouds plugin [38] was used. The plugin supports different point cloud file formats like E57 and PTS.

One of the challenges when using the point cloud data from the laser scans to the Unreal Engine was that the plugin reduces by default the number of points being visualized to improve the performance of the GPU; however, due to the high number of points included in the scan (over 30,000,000 points), the quality of the scans was reduced to a point where the scans resemble a chaotic (and useless) 3D model. To overcome this issue, this setting can be adjusted to increase the number of points being processed and visualized to improve the quality of the scans. To increase the number of points, users will need to modify the PointBudget variable in the C++ code of the plugin by typing "r.LidarPointCloudBudget" in the command line of the Unreal Engine and increasing this value. We have concluded that any value in the range of 8,000,000 to 10,000,000 points gives an acceptable quality for our model. More complex and bigger scans might need a higher budget to generate a quality 3D environment.

3.2. Real-time data acquisition

The data acquisition system employed in this case study comprises two distinct modules. The first module focuses on the installation of ambient sensors, which collect information including temperature, humidity, and particle concentration. In the second module, real-time detection of space occupancy is taken into consideration. This module utilizes a combination of a static camera and a computer vision algorithm to detect the presence of humans and accurately determine their location within the space.

Figure 2 shows the six locations selected to install two different types of ambient sensors (as described in the next subsection) and a camera for occupancy estimation.

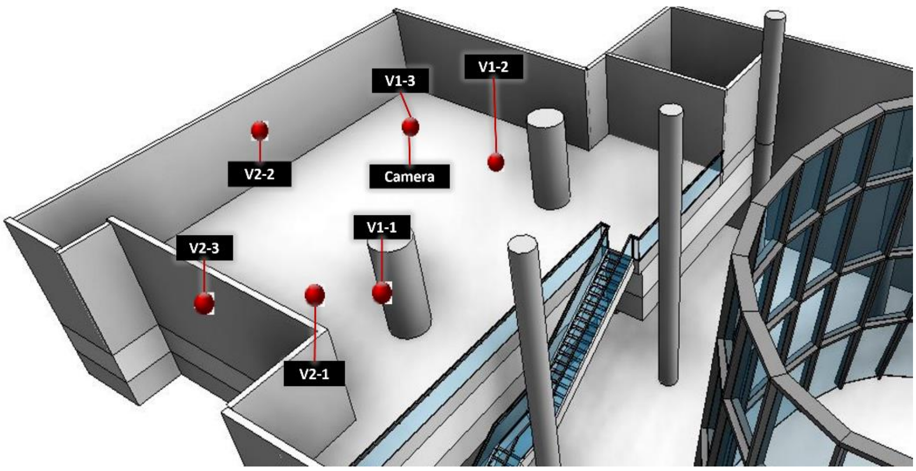


Figure 3: Location of data acquisition sensors used (Sensirion SEN55 (V1-1, V1-2, V1-3), BME280 (V2-1, V2-2 and V2-3) and camera.

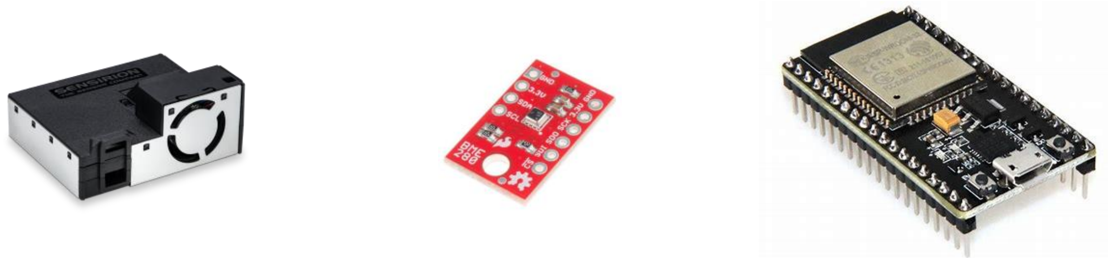
3.2.1. Ambient Sensors

Two different types of sensors (Sensirion and BME280) were developed to capture ambient information, including temperature, humidity, and particles (Figure 3). These sensors were specifically selected to actively engage students in the development process. Consequently, the installation of the sensors and the integration of various components were conducted within the laboratory setting. The different elements and main sensors built for this project are summarized next.

The Sensirion SEN55 sensor (Figure 4a) is an all-in-one sensor solution for the accurate measurement of various environmental parameters such as particulate matter, volatile organic compounds (VOCs), oxidizing gases such as nitrogen oxides (NOx), as well as humidity and temperature [39]. It features a 4.5V to 5.5V range, 63mA average current consumption at 5V, a long lifetime, high dust resistance thanks to sheath flow technology, and an I2C interface.

The BME280 (SEN-13676) (Figure 4b) is an atmospheric sensor breakout board that measures barometric pressure, humidity, and temperature readings without too much space. It gives you easy-to-solder 0.1” headers, runs I2C or SPI, takes measurements at less than 1mA and idles less than 5uA [40].

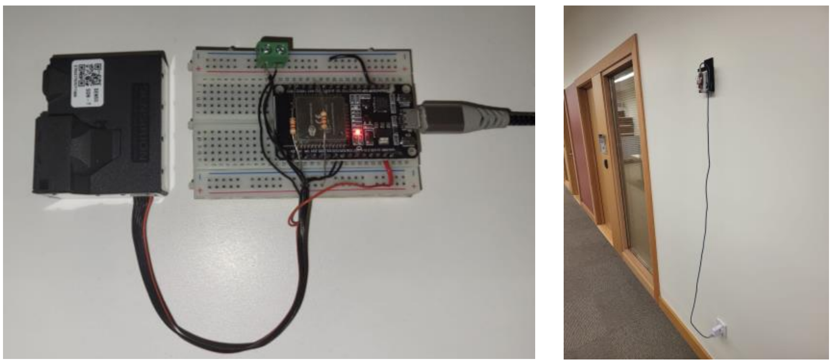
The ESP32 (Figure 4c) is a low-cost microcontroller with integrated Wi-Fi and Bluetooth that can be programmed with the Arduino IDE software [41]. It supports traditional communication protocols and HTTPS and has a crypto-accelerator.



(a) (b) (c)

Figure 4. View of the (a) Sensirion SEN55 [39], (b) BME280 (SEN 13676) [42], and (c) NodeMCU-32S ESP32 [43] used for the development of sensors

The sensors were mounted on breadboards using the ESP32 in Arduino Integrated Development Environment (IDE). An example of the Sensirion circuit connected to the ESP 32 via a breadboard is shown in (Figure 5). The board is powered through the micro USB port either by the laptop while programming or by the battery pack. A similar approach was done for the BME280.



(a) (b)

Figure 5. (a) View of the Sensirion SEN55 circuit mounted on a breadboard with the ESP32, (b) sample view of one of the sensors installed

3.2.2. Occupancy

To estimate the human occupancy in the space investigated, a system able to detect people inside of a room and estimate their positions within the room using a single Monocular Camera was used. Figure 6 shows an overview of the process for estimating the positioning of people in the space.

The occupancy estimation system initiates by capturing the camera feed, which is then subjected to two distinct algorithms for depth estimation and object detection. The TensorFlow object detection API [44] is utilized to identify individuals within the captured feed. Simultaneously, the camera feed is processed in parallel using the MiDaS [45] monocular depth estimation algorithm to estimate depth information. The results from these algorithms are combined, enabling the determination of the (near) real-time relative location of individuals within the video feed. Additionally, the same camera feed undergoes processing to detect the boundaries and center of the captured image. This information plays a crucial role in converting the depth mapping of detected individuals in the feed into global x-y positioning.

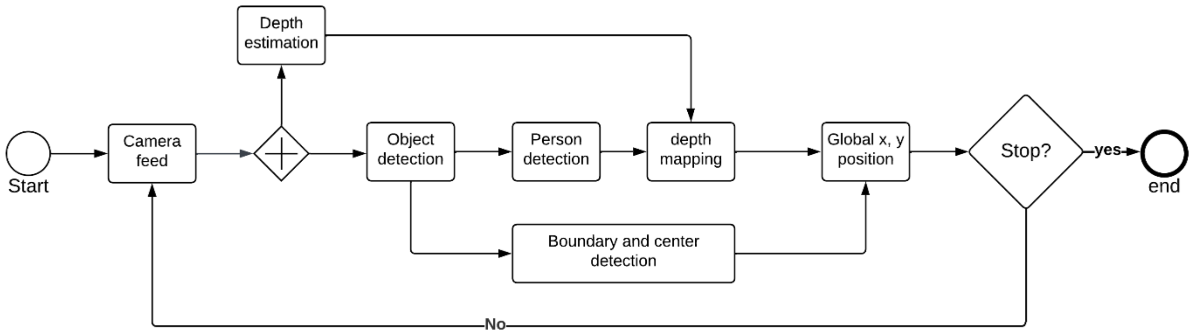


Figure 6. Overview of the process for occupation estimation

3.3. IoT Platform

The real-time data was streamed to the digital twin model using the ThingSpeak [46] IoT platform for the ambient sensors and automatically updating a Google spreadsheet template for occupancy estimation.

In the case of the ThingSpeak platform, a total of six channels representing a total of six sensors were created. The channels contain fields representing each data feed from the sensors. For instance, Sensirion sensors produce six readings: Temperature, Humidity, and particle concentration (PM1, PM2.5, PM4 and PM10) (Table 2). Each reading was registered in a distinct field on a channel. Similarly, the BME280 sensor produces Temperature, Humidity and Pressure data, which are streamed in a distinct channel field.

Table 2. Example of sensor's response data

Field Number	**Reading**
Field1	Temperature
Field2	Humidity
Field3	PM1.0
Field4	PM2.5
Field5	PM4.0
Field6	PM10.0

On the other hand, the occupancy estimation data was streamed to a Google Spreadsheet, which stored the X and Y coordinates of individuals occupying the space at the given moment. This data is continuously updated, replacing the previous readings every 15 seconds to maintain real-time accuracy.

3.4. Integration of physical space with the digital model

After the physical space has been instrumented, it has to be linked with the digital model. Once the real-time data captured from the sensors is pushed in JSON format, a node-based interface to create gameplay elements from within Unreal Editor (known as Blueprint scripts) was used to get the data in JSON format using the API. The VaRest [30] plugin for Unreal Engine was used in this case. This plugin includes functions allowing to get JSON data from APIs during runtime in the Unreal Engine editor.

Two main Blueprint scripts were developed to implement the flow of information from the sensors and the occupancy estimation. The first Blueprint script was used to obtain the sensor data in JSON format from the ThingSpeak API, while the second Blueprint was used to obtain the occupant's locations from the Google Sheets API.

3.4.1. Blueprint script to obtain the sensor data in JSON format from the ThingSpeak API

The first step to accessing the sensor data was establishing the connection between the Unreal Engine environment and the ThingSpeak API. This was achieved by using the *Call URL* function from the

VaRest plugin. The required input for these functions is the API URL and setting the function to GET the JSON data. The Response Event was used to activate this function and to pull the JSON data from the API. The *Get Response Content as String* function was used to extract the call response in JSON format, which outputs the obtained JSON data in a string format. The second step was to obtain the required data from the JSON response. The JSON response includes an array with six fields, each corresponding to a different reading from the sensor (Table 2).

To obtain the required field or the required reading, a custom function was developed in Blueprints (labeled *JSON Value Getter*). The function has four main inputs and a single output. The single output of the function is the reading value (e.g., temperature, humidity, etc.). The inputs of the function are summarized in Table 3. Figure 7 shows a sample of the Blueprint code to get the temperature reading from one of the sensors. As seen in Figure 7, the first code block (Call URL) is used to obtain the URL of the API with the data. The *Response Event* block initiates the connection between the API and the application. The following code block (*Get Response Content as String*) obtains the API data in JSON format. Finally, the *JSON Value Getter* takes as input the required fields listed in Table 3 and outputs the specific sensor value listed in Table 2.

Table 3. Sensor's Response Data and JSON Function Inputs

Input Variable	Description
Array Name	The name of the array in the JSON response as obtained from ThingSpeak
Array Index	The index of the array in case there are several arrays (0 for our case as we are obtaining the first array)
Field Name	The field name of the reading we want as described in Table 2
Response Node	The JSON request event which holds the JSON data object (Response Event)

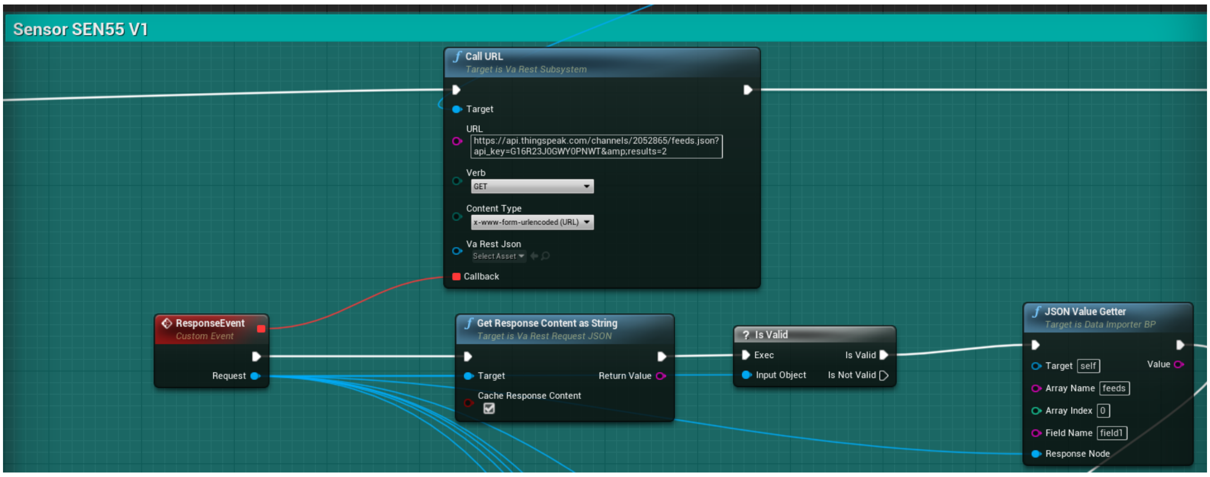


Figure 7. Sensor Data Blueprint

3.4.2. Blueprint to obtain the occupant's locations from the Google Sheets API

The main role of this function is to obtain the number of occupants currently in the room and their specific coordinates within the room on the Google Sheet. The first step is the same as explained above, and the same functions were used to obtain the data in JSON format from the Google Sheet. The only difference was that the URL was replaced by the Google Sheet JSON URL. The second step required a different approach since each row in the Google Sheet is stored as a different array in the JSON object. However, the challenge is that each row does not have a unique field name to obtain the data from in the same way as the sensor data. Each row of data is stored in a single array, and all arrays are stored in a general array having a field name as values. To obtain each row's X and Y coordinate values (each row represents a person in the office space), the *For Each Loop* function was used to loop over each row and obtain the X and Y values from it. The Blueprint script to obtain the Google Sheet data is shown in Figure 8.

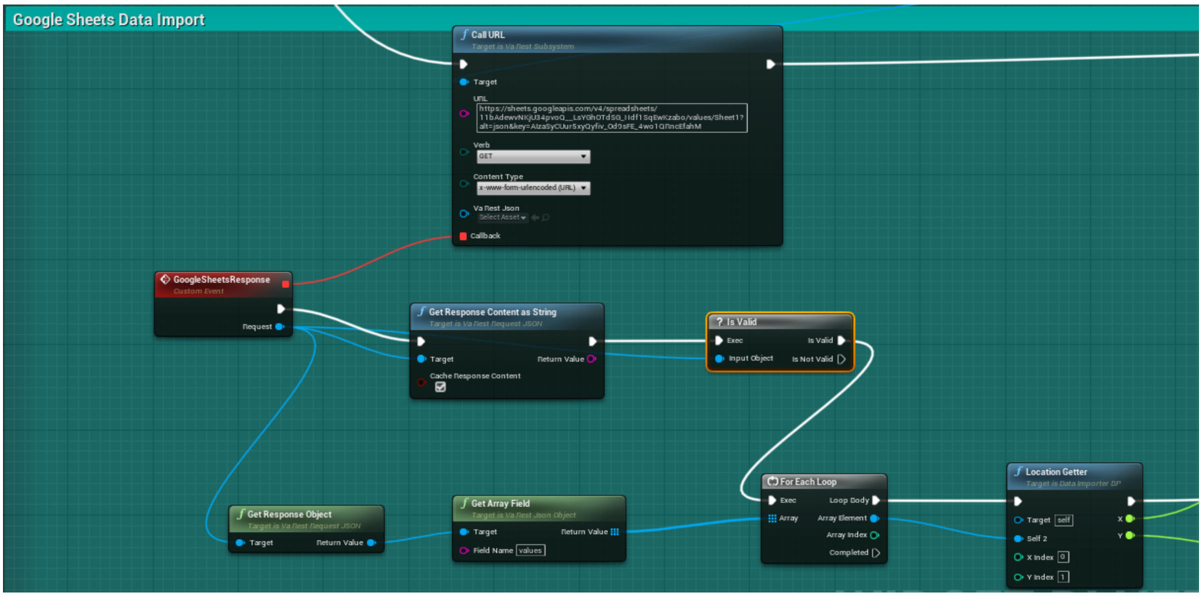


Figure 8. Google Sheet Data Blueprint

3.5. Results: Data visualization

After securing the connection and flow of data from the sensors to the Unreal Engine environment using the Blueprint scripts, the final step for the digital twin development is to visualize the data (i.e., use it as a cockpit or dashboard with information collected from the sensors). This is a key element since it will allow a better understanding of the real-time information of the different elements monitored.

An example of the visualization of the data is shown in Figure 9 (for temperature), Figure 10 (for air quality), and Figure 11 (for occupancy).

Three different sensors were used to monitor and display the temperature, each located in a zone within the space considered for this study. To ensure the occupants' comfort, a value for the office temperature was set to stay between 22 and 23 degrees Celsius. Any value above or below this range was considered out of the comfort range of the occupants and thus was color-coded based on its value. Green was used to indicate an optimum working temperature in the office, orange was used to indicate a change in the temperature, and red was used to indicate a large change (more than 2 degrees from the comfort range defined for this study) in the office temperature.

Based on the real-time data captured from the sensors, the different zones in the office space were color-coded. That can be seen in Figure 9, where Zone 3 is color-coded in orange, meaning there is a slight increase in the ideal temperature in that specific zone, while Zones 1 and 2 are color-coded in red, indicating that both zones have more than 2 degrees of change in temperature from the comfort range. In addition to the color coding of the zones, a bar chart is updated based on the real-time data and integrated into the model to visualize the change in temperature values among the predetermined zones.

Figure 9. Screenshot of the visualization in the Unreal Engine displaying the Office Zoning Color Coding based on temperature readings from the sensors

For the monitoring and display of the air quality as indicated by the PM values, a simple dashboard summarizing the readings along with the safe values for each reading was added to the digital twin (Figure 10). Also, since PM2.5 is considered the most dangerous to human health, a line chart showing the changes in the PM2.5 value was added to the digital twin.

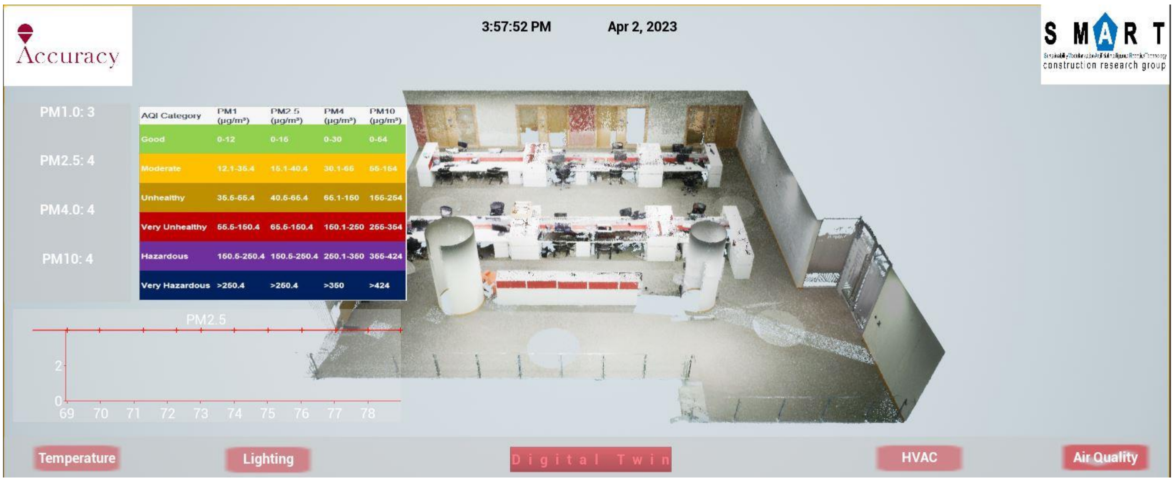


Figure 10. Screenshot of the visualization in the Unreal Engine related to the air quality information

The script for the visualization of the occupancy rate is shown in Figure 8. The first step is to obtain each occupant's location (X and Y coordinates) in the room. This information is sent to a Google Sheet. Afterward, the script spawns or adds a game object, in this case, the 3D avatars shown in Figure 10, to the coordinates. This code is refreshed every 5 to 10 seconds to update the occupants' locations in real-time.

4. Discussion and limitations

Digital twins offer a valuable tool for the AEC industry to optimize the performance of buildings through their lifecycle. By creating a digital representation of physical spaces, building managers can simulate various scenarios to improve energy efficiency, air quality and waste reduction. This can lead to more sustainable building systems.

This study demonstrated the construction of a digital twin model of an indoor space using various reality capture technologies, student-designed and built sensors and an IoT platform. The utilized laser scanner technologies to capture the geometric and color data of the physical environment are selected based on their specific capabilities and advantages, such as reducing occlusion or capturing color data.

Although this process allows to accurately represent the space, processing dense point clouds becomes computationally heavy and working with Unreal Engine was challenging.

Figure 11. Screenshot of the visualization in the Unreal Engine showing the occupancy in the area of interest

Another significant aspect discussed in the study is the real-time data acquisition process. The installed ambient sensors generally collect information such as temperature, humidity, and particle concentration. For a broader understanding of energy efficiency or air quality, a given space can be improved by adding sensors with more parameters (i.e., carbon monoxide concentration, and electric power consumption). However, the data streaming platform utilized in the study, ThingSpeak, provides a fixed number of channels that limit the system's scalability.

The study further discusses the integration of the physical space with the digital model, particularly the use of Unreal Engine, plugins, and Blueprint scripts to link the real-time data obtained from the sensors and occupancy estimation with the digital twin model. They demonstrated obtaining sensor data in JSON format from the ThingSpeak API and occupant location data from the Google Sheets API. This integration enables real-time data visualization within the digital twin, providing a comprehensive and interactive representation of the physical space.

In this proof-of-concept study, a key objective was to engage students in the development of the sensor systems and their integration with the digital model. Therefore, instead of utilizing commercial solutions to perform sensing, students were able to gain a full learning experience by building sensors using basic modules. Initially, the aim was to create sensors that could operate on battery power. This had some limitations primarily related to power source optimization, but it was a great learning experience for the students involved. To address this limitation, the sensors were strategically placed where power outlets were available, allowing them to be powered directly.

5. Conclusions and outlook

Digital twin technology has gained much attention in recent years as it provides a virtual replica of a physical asset or system that can be used to simulate and optimize performance. However, implementing digital twins in the built environment can be challenging for several reasons. For example, digital twins rely on data from sensors and other sources to accurately represent the physical system. However, this data can be difficult to collect and may not always be accurate, leading to potential errors in the digital twin model. Digital twins must be integrated with existing systems for real-time monitoring and analysis. This can be challenging, as many legacy systems were not designed to work with digital twins. Operating digital twins requires significant computational resources, and scaling up to represent larger systems can be challenging. Therefore, careful planning and optimization are needed to ensure the digital twin can handle the required workload. Security becomes important since digital twins can contain sensitive data about the physical system, making them a potential target for cyber-attacks [47]. Security measures must be implemented to protect the digital twin from unauthorized access. Digital twins need to be able to work with other systems and software to provide a comprehensive view of the physical system. This requires standards and protocols to ensure data can be shared between systems. Finally, implementing digital twins can be expensive. They might require significant investments in hardware, software, and personnel to develop and maintain the system.

Future work includes adding other features/sensors and visualization. For example, lighting and HVAC. For lighting, Light Actors can be placed in the scene, which are turned on or off based on their real-time status in the office. As for the HVAC system, the visualization also turns on and off based on the actual status of the system. To visualize the intensity and airflow of the HVAC system, the Niagara system in Unreal Engine can be used. For instance, a colored air flow moving from the location of the HVAC register output (usually in the ceiling or upper portion of a wall) increases in intensity based on the airflow value set in the office. An example of how the visualization of the airflow would be seen in the digital twin is shown in Figure 12.

Figure 12. Airflow Visualization

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References

[1] European Commission. Directorate General for Research and Innovation., *Industry 5.0: human centric, sustainable and resilient.* LU: Publications Office, 2020. Accessed: May 10, 2023. [Online]. Available: https://data.europa.eu/doi/10.2777/073781
[2] H. Feng, Q. Chen, and B. Garcia de Soto, "Application of digital twin technologies in construction: an overview of opportunities and challenges," presented at the 38th International Symposium on Automation and Robotics in Construction, Dubai, UAE, Nov. 2021. doi: 10.22260/ISARC2021/0132.
[3] R. Bortolini, R. Rodrigues, H. Alavi, L. F. D. Vecchia, and N. Forcada, "Digital Twins' Applications for Building Energy Efficiency: A Review," *Energies*, vol. 15, no. 19, p. 7002, Sep. 2022, doi: 10.3390/en15197002.
[4] J. K. Dickinson, P. Woodard, R. Canas, S. Ahamed, and D. Lockston, "Game-based trench safety education: Development and lessons learned," *Electronic Journal of Information Technology in Construction*, vol. 16, no. March 2010, pp. 118–132, 2011.
[5] H. Li, G. Chan, and M. Skitmore, "Visualizing safety assessment by integrating the use of game technology," in *Automation in Construction*, Elsevier, Mar. 2011, pp. 498–505. doi: 10.1016/j.autcon.2011.11.009.
[6] L. K.Y, R. A. G., L. C.H, and D. L. L. J, "Developing 3D Safety Training Materials on Fall Related Hazards for Limited English Proficiency and Low Literacy Construction Workers," in *Computing in Civil Engineering*, 2012, pp. 1–25.
[7] L. Yuan-Ling, L. Ken-Yu, L. Min, and C. Nai-Wen, "Learning Assessment Strategies for an Educational Construction Safety Video Game," in *Construction Research Congress*, 2012, pp. 2091–2100.
[8] Y. Fang, J. Teizer, and E. Marks, "A Framework for Developing As-Built Virtual Enviroments to Advance Training of Crane Operators," in *Construction Research Congress 2014*, 2014, pp. 140–149. doi: 10.1061/9780784413517.176.

[9] Q. Le, A. Pedro, C. Lim, H. Park, C. Park, and H. Kim, “A framework for using mobile based virtual reality and augmented reality for experiential construction safety education,” *The International journal of engineering education*, vol. 31, no. 3, pp. 713–725, 2015.

[10] A. Pedro, Q. T. Le, and C. S. Park, “Framework for Integrating Safety into Construction Methods Education through Interactive Virtual Reality,” *Journal of Professional Issues in Engineering Education and Practice*, vol. 142, no. 2, pp. 1–10, 2016, doi: 10.1061/(ASCE)EI.1943-5541.0000261.

[11] Z. Liang, K. Zhou, and K. Gao, “Development of Virtual Reality Serious Game for Underground Rock-Related Hazards Safety Training,” *IEEE Access*, vol. 7, pp. 118639–118649, Aug. 2019, doi: 10.1109/access.2019.2934990.

[12] C. Zhang and B. Chen, “Enhancing Learning and Teaching for Architectural Engineering Students uing Virtual Building Design and Construction,” *Higher Education Studies*, vol. 9, no. 2, p. 45, 2019, doi: 10.5539/hes.v9n2p45.

[13] R. Eiris, M. Gheisari, and B. Esmaeili, “Desktop-based safety training using 360-degree panorama and static virtual reality techniques: A comparative experimental study,” *Automation in Construction*, vol. 109, no. May 2019, p. 102969, 2020, doi: 10.1016/j.autcon.2019.102969.

[14] O. Golovina, C. Kazanci, J. Teizer, and M. König, “Using Serious Games in Virtual Reality for Automated Close Call and Contact Collision Analysis in Construction Safety,” in *Proceedings of the 36th International Symposium on Automation and Robotics in Construction (ISARC)*, 2019. doi: 10.22260/isarc2019/0129.

[15] S. Bükrü, M. Wolf, O. Golovina, and J. Teizer, “Using Field of View and Eye Tracking for Feedback Generation in an Augmented Virtuality Safety Training,” in *Construction Research Congress 2020: Safety, Workforce, and Education*, American Society of Civil Engineers Reston, VA, 2020, pp. 625–632.

[16] C. S. Park, Q. T. Le, A. Pedro, and C. R. Lim, “Interactive Building Anatomy Modeling for Experiential Building Construction Education,” *Journal of Professional Issues in Engineering Education and Practice*, vol. 142, no. 3, pp. 1–12, 2016, doi: 10.1061/(ASCE)EI.1943-5541.0000268.

[17] L. Messi, B. García de Soto, A. Carbonari, and B. Naticchia, “Spatial conflict simulator using game engine technology and Bayesian networks for workspace management,” *Automation in Construction*, vol. 144, p. 104596, Dec. 2022, doi: 10.1016/j.autcon.2022.104596.

[18] L. Messi, B. García de Soto, A. Carbonari, and B. Naticchia, “Intelligent BIM-based spatial conflict simulators: A comparison with commercial 4D tools,” presented at the 39th International Symposium on Automation and Robotics in Construction, Jul. 2022. doi: 10.22260/ISARC2022/0078.

[19] K. Wu and B. García de Soto, “Spatio-temporal planning simulation of temporary elevators in construction using a game engine,” presented at the 38th International Symposium on Automation and Robotics in Construction, Dubai, UAE, Nov. 2021. doi: 10.22260/ISARC2021/0042.

[20] A. Ezzeddine and B. García de Soto, “Connecting teams in modular construction projects using game engine technology,” *Automation in Construction*, vol. 132, pp. 103887–103887, Dec. 2021, doi: 10.1016/j.autcon.2021.103887.

[21] R. Sacks, I. Brilakis, E. Pikas, H. S. Xie, and M. Girolami, “Construction with digital twin information systems,” *DCE*, vol. 1, p. e14, 2020, doi: 10.1017/dce.2020.16.

[22] Mike Shafto *et al.*, “Modeling, Simulation, Information Technology and Processing Roadmap,” National Aeronautics and Space Administration (NASA), Washington, DC 20546, DRAFT, Apr. 2012. Accessed: May 10, 2023. [Online]. Available: https://www.nasa.gov/sites/default/files/501321main_TA11-ID_rev4_NRC-wTASR.pdf

[23] M. W. Grieves, “Virtually Intelligent Product Systems: Digital and Physical Twins,” in *Complex Systems Engineering: Theory and Practice*, S. Flumerfelt, K. G. Schwartz, D. Mavris, and S. Briceno, Eds., Reston, VA: American Institute of Aeronautics and Astronautics, Inc., 2019, pp. 175–200. doi: 10.2514/5.9781624105654.0175.0200.

[24] S. Greengard, “Digital Twins Grow Up,” Aug. 06, 2019. https://cacm.acm.org/news/238642-digital-twins-grow-up/fulltext (accessed May 10, 2023).

[25] V. J. Mawson and B. R. Hughes, “The development of modelling tools to improve energy efficiency in manufacturing processes and systems,” *Journal of Manufacturing Systems*, vol. 51, pp. 95–105, Apr. 2019, doi: 10.1016/j.jmsy.2019.04.008.

[26] B. Schleich, N. Anwer, L. Mathieu, and S. Wartzack, “Shaping the digital twin for design and production engineering,” *CIRP Annals*, vol. 66, no. 1, pp. 141–144, 2017, doi: 10.1016/j.cirp.2017.04.040.

[27] J. Zhao, H. Feng, Q. Chen, and B. Garcia de Soto, “Developing a conceptual framework for the application of digital twin technologies to revamp building operation and maintenance processes,” *Journal of Building Engineering*, vol. 49, p. 104028, May 2022, doi: 10.1016/j.jobe.2022.104028.

[28] OECD, “Climate-resilient infrastructure,” OECD Environment Policy Papers 14, Dec. 2018. doi: 10.1787/4fdf9eaf-en.

[29] Anonymous, “Research Profile - Staffordshire Bridges – long-term performance monitoring using fibre optic sensors,” Sep. 22, 2022. https://www.cdbb.cam.ac.uk/news/research-profile-staffordshire-bridges-long-term-performance-monitoring-using-fibre-optic (accessed May 19, 2023).

[30] Anonymous, “Digital Twin Journeys: smart infrastructure for safety and reliability across the rail network,” Nov. 22, 2021. https://www.cdbb.cam.ac.uk/news/digital-twin-journeys-smart-infrastructure-safety-and-reliability-across-rail-network (accessed May 19, 2023).

[31] J. H. Flynn, B. Crudele, and J. M. Fuda, “East 138th Street Bridge Replacement Project: A Marriage of ABC and Digital Delivery at NYSDOT | Accelerated Bridge Construction.” https://abc-utc.fiu.edu/mc-events/east-138th-street-bridge-replacement-project-a-marriage-of-abc-and-digital-delivery-at-nysdot/?mc_id=789 (accessed May 10, 2023).

[32] domlysz, “Blender GIS.” May 10, 2023. Accessed: May 10, 2023. [Online]. Available: https://github.com/domlysz/BlenderGIS

[33] Center for Interacting Urban Networks (CITIES), “CITIESair.” https://citiesair.com/ (accessed May 20, 2023).

[34] “Leica BLK360 Imaging Laser Scanner.” https://leica-geosystems.com/products/laser-scanners/scanners/blk360 (accessed May 20, 2023).

[35] “FARO Focus Laser Scanner | FARO.” https://knowledge.faro.com/Hardware/Focus/Focus/Technical_Specification_Sheet_for_the_Focus_Laser_Scanner (accessed May 20, 2023).

[36] “Hovermap Series,” *Emesent*. https://emesent.com/hovermap-series/ (accessed May 20, 2023).

[37] Unreal Engine, “Unreal Engine | The most powerful real-time 3D creation tool,” *Unreal Engine*. https://www.unrealengine.com/ (accessed May 10, 2023).

[38] Unreal Engine, “LiDAR Point Cloud Plugin,” *Unreal Engine 5.0 Documentation - LiDAR Point Cloud Plugin*. https://docs.unrealengine.com/5.0/en-US/lidar-point-cloud-plugin-for-unreal-engine/ (accessed May 10, 2023).

[39] Sensirion, “Smart sensor solutions,” *SEN55: Environmental sensor node for PM, RH/T, VOC, NOx measurements*. https://sensirion.com/products/catalog/SEN55/ (accessed May 20, 2023).

[40] “SparkFun BME280 Arduino Library.” SparkFun Electronics, May 01, 2023. Accessed: May 20, 2023. [Online]. Available: https://github.com/sparkfun/SparkFun_BME280_Arduino_Library

[41] “Arduino core for the ESP32, ESP32-S2, ESP32-S3 and ESP32-C3.” Espressif Systems, May 20, 2023. Accessed: May 20, 2023. [Online]. Available: https://github.com/espressif/arduino-esp32

[42] "BME280 Combined humidity and pressure sensor: Final data sheet." BOSCH, May 07, 2015. Accessed: May 20, 2023. [Online]. Available: https://cdn.sparkfun.com/assets/learn_tutorials/4/1/9/BST-BME280_DS001-10.pdf
[43] "NodeMCU-32S - Waveshare Wiki." https://www.waveshare.com/wiki/NodeMCU-32S (accessed May 20, 2023).
[44] Hongkun Yu Chen Chen, Xianzhi Du, Yeqing Li, Abdullah Rashwan, Le Hou, Pengchong Jin, Fan Yang, Frederick Liu, Jaeyoun Kim and J. Li, "TensorFlow Model Garden." 2020. [Online]. Available: https://github.com/tensorflow/models
[45] R. Ranftl, K. Lasinger, D. Hafner, K. Schindler, and V. Koltun, "Towards Robust Monocular Depth Estimation: Mixing Datasets for Zero-Shot Cross-Dataset Transfer," *IEEE Transactions on Pattern Analysis and Machine Intelligence*, vol. 44, no. 3, 2022.
[46] "IoT Analytics - ThingSpeak Internet of Things." https://thingspeak.com/ (accessed May 22, 2023).
[47] B. García de Soto, A. Georgescu, B. Mantha, Ž. Turk, A. Maciel, and M. Semih Sonkor, "Construction cybersecurity and critical infrastructure protection: new horizons for Construction 4.0," *ITcon*, vol. 27, pp. 571–594, Jun. 2022, doi: 10.36680/j.itcon.2022.028.

IMPLEMENTATION OF WIRELESS AND SENSING TECHNOLOGIES IN HIGHWAY PROJECTS: A SWOT APPROACH

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Abstract

The demand for safe, reliable, and higher-quality transportation and infrastructure systems often increases the complexity of constructing and maintaining highway projects and pressures Departments of Transportation (DOTs) to finish projects on tighter schedules and stricter budgets. Such complexities necessitate the use of technologies when constructing and maintaining transportation assets, notably wireless and sensing technologies. For the last few years, DOTs' use of wireless and sensing technologies has been on the rise, with numerous research efforts aiming to explore applications and investigate case studies. Thus, this study buildings on the existing body of knowledge to develop a holistic Strengths Weaknesses Opportunities Threats (SWOT) framework that aims to comprehensively understand the implementation of eight wireless and sensing technologies in highway projects including barcodes and readers, Radio Frequency Identification (RFID), e-ticketing, Ground Penetrating Radar (GPR), Unmanned Aerial Systems (UAS) or Vehicles (UAV) or Drones, Light Detection and Ranging (LiDAR), Geographic Information System (GIS), and Global Positioning System or Global Navigation Satellite System (GNSS). The SWOT framework was developed via literature and then distributed via an online survey to subject matter experts in different DOTs. Results from the survey provided comprehensive insights into the strengths of using the technologies in the project's construction and asset management phases, the weaknesses that these technologies may face, the opportunities that they provide DOTs with, and the threats that the DOTs may need to overcome for successful implementation.

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Keywords: construction; asset management; departments of transportation; highway projects; technology

1. Introduction

State Departments of Transportation (DOTs) across the United States have been undergoing major transformations to adopt technology and digitize the design, construction, delivery, and operation of construction projects [1]–[3]. Such transformations have rapidly accelerated in the last few years with the national push to digitize asset data and the increase in investments to repair and renew the aging infrastructure [4], [5].

Wireless and sensing technologies are at the forefront of the technologies making waves in infrastructure projects due to the critical role they play in monitoring, managing, and maintaining existing transportation assets [5]–[7]. Moreover, the success of complex infrastructure projects requires project information and data to be accurate, complete, readily available, gathered promptly, shared in an easily understood format among stakeholders, and stored safely and securely – paving the way for the diverse use of wireless and sensing technologies [8], [9].

State DOTs have been adopting and using wireless and sensing technologies in various use cases that enable them to identify, gather, locate, track, measure, save, document, and transmit information in real-time or near real-time [10]. With this adoption expected to increase, the objective of this paper is to understand DOTs' experience with wireless and sensing technologies and provide insights into the technologies' roles in highway infrastructure projects.

2. Research Methodology

This paper focuses on eight technologies that have gained traction within state DOTs: barcodes and readers, Radio Frequency Identification (RFID), e-ticketing, Ground Penetrating Radar (GPR), Unmanned Aerial Systems (UAS) or Vehicles (UAV) or Drones, Light Detection and Ranging (LiDAR), Geographic Information System (GIS), and Global Positioning System or Global Navigation Satellite System (GNSS). To achieve the research objective, a comprehensive SWOT framework was developed to identify the:

- Strengths of using each of the technologies in the construction and asset management phases of the project;
- Weaknesses that these technologies may face;
- Opportunities that they provide DOTs with;
- Threats that the DOTs may need to overcome for successful implementation.

A survey was developed and shared with subject-matter experts across the different DOTs through the AASHTO Committee on Construction, AASHTO Committee on Maintenance, and the AASHTO Subcommittee on Asset Management. The survey aimed to collect data on each aspect of the SWOT framework. Statistical tests were then performed to analyze findings and draw conclusions.

2.1. The SWOT Framework

SWOT framework is a simple yet powerful tool that can be used by decision-makers in the early stages of business planning to develop strategies and support decision-making [11], [12]. Strengths and weaknesses are internal factors, while opportunities and threats have an external nature [11], [12]. SWOT analysis has been extensively used in research studies targeting different industries such as oil and gas, mining, manufacturing, agriculture, transportation, food and nutrition, and construction [13], [14]. In the context of adopting technologies in the construction industry, SWOT analysis can provide organizations with a deep understanding of the possibilities of exploiting the technology's strengths and overcoming its weaknesses to take advantage of the opportunities it provides to the organization while limiting the risks that it can bring [12]. As such, the internal factors of SWOT – i.e., strengths and weaknesses – are directly related to the technology itself, while the external factors – i.e., opportunities and threats – relate to the context of the application of the technology in construction organizations [15].

The ability of the SWOT technique to address and analyze both internal and external factors makes it highly suitable for providing construction academicians and practitioners with a holistic review of the technology and its applications [15]. Examples of using SWOT analysis for construction technologies include Building Information Modeling (BIM) [12], machine learning [16], blockchain [17], [18], robotics and drones [19], and virtual reality [20]. As the method is deemed successful in construction research, this paper employs SWOT analysis to provide a holistic review of the use of wireless and sensing technologies in highway projects. To identify the SWOT aspects affecting each of the eight technologies targeted in this study, a general framework was comprehensively developed from existing state-of-adoption research on the topic [10], [21].

2.1.1. Strengths

Strengths are regarded as the internal factors that render wireless and sensing technologies important in highway projects. This can translate to the major use cases that the technologies can add value when used across the lifecycle of highway projects. For the strength aspect, two major project phases were considered: construction and asset management. The strength of sensing and wireless technologies depends on their application through the construction project lifecycle, but the nature of the work performed during construction is different from that performed during asset management. Thus, to better analyze the impact of sensing and wireless technologies, the strengths that such technologies bring to the construction and asset management phases were extensively identified as presented in Table 1.

Table 1. Strengths of wireless and sensing technologies.

Code	Strengths	Code	Strengths
S-C1	Tracking position of bulk material in transit or for haul route compliance	S-C21	Locating rebar
S-C2	Tracking of finished materials and inventory	S-C22	Finding underground voids
S-C3	Monitoring or determining project progress/production	S-C23	Erosion control inspection
S-C4	Locating haulers at fixed points (plant/ project/ paver/ dump location)	S-C24	Measuring spot temperatures
S-C5	Locating underground utilities and assets	S-C25	Creating temperature map
S-C6	Density measurements	S-A1	Locating pavement/material placement for performance tracking
S-C7	Thickness measurement of pavements	S-A2	Sign, culvert, and other asset inventories
S-C8	Tracking and monitoring construction vehicles and equipment on site	S-A3	Sharing asset information between different functional units
S-C9	Tool tracking/ Theft control	S-A4	Pavement crack and defect detection
S-C10	Documenting material quantities for pay	S-A5	Sign, culvert, and another asset inspection
S-C11	Smart Work Zone	S-A6	Structure inspection
S-C12	Automated Machine Guidance	S-A7	Slope stability & landslide assessment
S-C14	Developing 3D as-built models	S-A8	Location of voids
S-C15	Collecting as-built information/ mapping of assets	S-A9	Location of buried assets
S-C16	Site photos & videos	S-A10	Rebar deterioration
S-C17	Structural inspection	S-A11	As-built development
S-C18	Remote (underground or confined space) inspection or modeling	S-A12	Guardrail assessment
S-C19	Earthwork inspection and quantities	S-A13	Site/ Right-of-Way (ROW) Survey
S-C20	Creating terrain models		

2.1.2. Weaknesses

Weaknesses, like strengths, are internal factors that are directly related to the use of wireless and sensing technologies. However, unlike strengths, weaknesses reflect the hardships, limitations, or technical breakdowns that the technologies may run into. The weaknesses are presented in Table 2.

Table 2. Weaknesses of wireless and sensing technologies.

Code	Weaknesses	Code	Weaknesses
W1	Loss of connectivity	W4	Integrating with current project administration systems
W2	System Defects	W5	Integrating with plant/supplier information technology (IT) system
W3	Accessibility for users	W6	Data transfer and interoperability issues

2.1.3. Opportunities

Opportunities are external factors that reflect the benefits and positive aspects that wireless and sensing technologies provide to DOTs. Nine opportunities were identified and listed in Table 3.

Table 3. Opportunities of wireless and sensing technologies.

Code	Opportunities	Code	Opportunities
O1	Quality Improvement	O6	Safety Enhancement
O2	Data Collection, Integration, and Management	O7	Cost Reductions
O3	Tracking Capabilities	O8	Schedule Acceleration
O4	Efficiency/Productivity Enhancement	O9	Decision-Making Enhancement
O5	Communication Effectiveness		

2.1.4. Threats

Threats are external factors that reflect the negative aspects that may hinder using the wireless and sensing technologies as well as challenges that organizations may need to overcome for successful technology implementation. Six threats were identified and listed in Table 4.

Table 4. Threats of wireless and sensing technologies.

Code	Threats	Code	Threats
T1	Resistance from third parties and vendors	T4	Lack of needed support technology
T2	Workforce skillset limitations or resistance	T5	Organizational culture (non-tech oriented)
T3	Investment costs or unknown return on investment	T6	Policy/regulation restrictions

2.2. Chi-Squared Test for Equal Likelihood

To examine if the eight sensing and wireless technologies identified in this study perform similarly across the four components of SWOT, the Chi-Squared Test for Equal Likelihood was employed. The data was organized into contingency tables for every SWOT category and the analysis was performed via R studio to detect significance with a 95% confidence level.

3. Results

A total of 24 responses were gathered from the 19 DOTs as highlighted in Figure 2. Almost half the respondents (50%) worked in the construction division, while the other half varied between asset management and maintenance (21%), IT (5%), across the three divisions (12%), or other divisions (12%) including design, surveying, and project delivery. As for the respondents' roles, most of them were construction engineers or engineering managers (54%), followed by technical support (9%), material engineers (4%), and other roles (33%) including system chiefs, innovation engineers, researchers, and maintenance engineers.

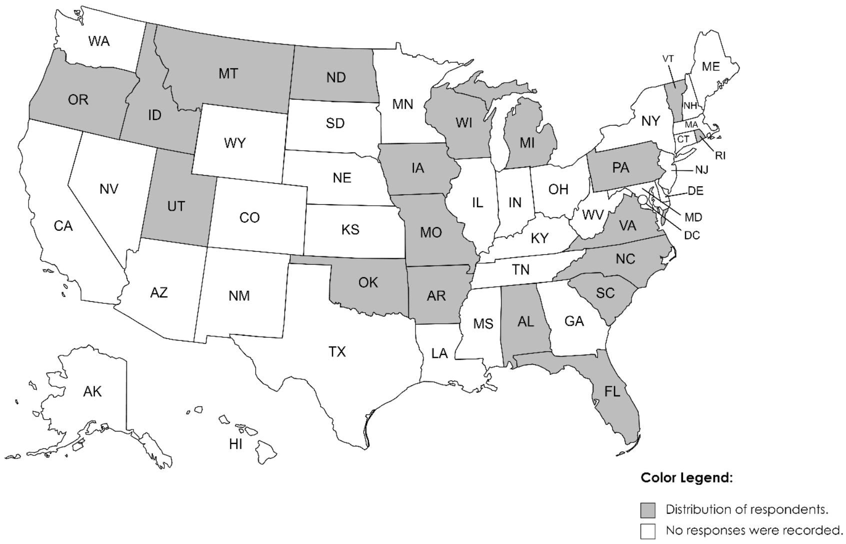


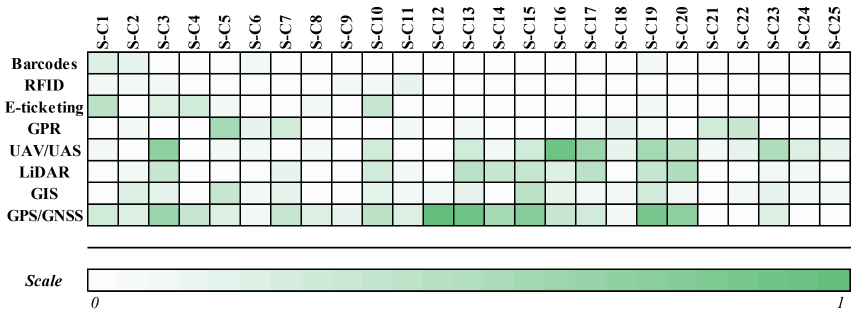
Figure 1 Distribution of survey responses (created with MapChart.net).

3.1. Results for Strengths

The distribution of strengths regarding "construction" is shown in Figure 3, while the distribution of strengths for "asset management" is shown in Figure 4.

Based on the normalized heatmap of the construction phase (Figure 3), GPS/GNSS, GIS, and UAV/UAS were the three technologies with the widest range of strengths, with results showing that GPS/GNSS was used for 21 of the 25 use-cases, while GIS and UAV/UAS were used for 19 of the 25 use-cases each. The three technologies with the lowest range of strengths were barcodes, RFID, and e-ticketing, with results showing that barcodes were used for 4 of the 25 use cases, while RFID and e-ticketing were used for 6 and 7 of the 25 use cases respectively.

The Chi-Square test for equal likelihood was significant for GPR (p-value = 0.038, i.e., significant with 95% confidence), UAV/UAS (p-value = 0, i.e., significant with 95% confidence), and GPS/GNSS (p-value = 0, i.e., significant with 95% confidence). For GPR, the darker intensity of S-C5 indicates that DOTs that used GPR were more likely to use it for locating underground utilities and underground assets than any other selected use cases. For UAV/UAS, the darker intensity of S-C3 and S-C16 indicates that DOTs were more likely to use UAV/UAS for monitoring or determining project progress and capturing site photos and videos than other selected use cases. As for GPS/GNSS, the darker intensity of S-C12, S-C13, S-C15, S-C19, and S-C20 indicates that DOTs were more likely to use GPS/GNSS for Automated Machine Guidance, site/ ROW survey, collecting as-built information and mapping of assets, earthwork inspection and quantities, and creating terrain models more than other selected use-cases.

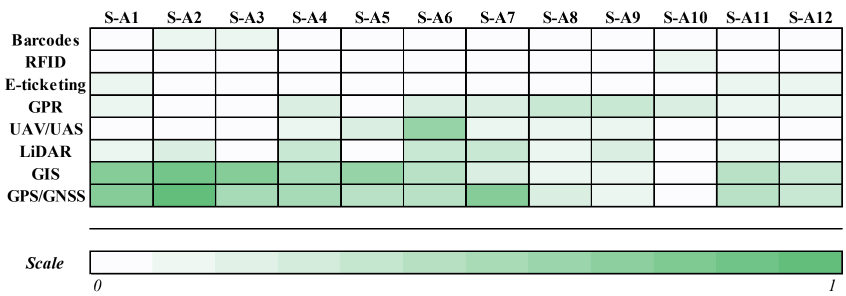


Chi-Square	DF	p-value	
1.57	3	0.67	
0.71	5	0.98	
8.67	6	0.19	
19.13	10	**0.038**	***
56.32	18	**0**	***
16.38	13	0.22	
18.97	18	0.39	
54.59	20	**0**	***

Figure 2. Distribution of Strengths in Construction and results of the Chi-Square Test for equal likelihood.

Based on the normalized heatmap of the asset management phase (Figure 4), GPS/GNSS, GIS, and GPR were the three technologies with the widest range of strengths, with results showing that GPS/GNSS and GIS were used for 11 of the 12 use-cases each, while GPR was used for 9 of the 12 use-cases. The three technologies with the lowest range of strengths were barcodes, RFID, and e-ticketing, with results showing that e-ticketing was used for 3 of the 12 use cases, while RFID and barcodes were used for 2 of the 12 use cases each.

The Chi-Square test for equal likelihood was significant for UAV/UAS (p-value = 0.08 so significant with 90% confidence). The darker intensity of S-A6 indicates that DOTs who used UAV/UAS in the asset management phase were more likely to use it for structure inspection than any other selected use cases.



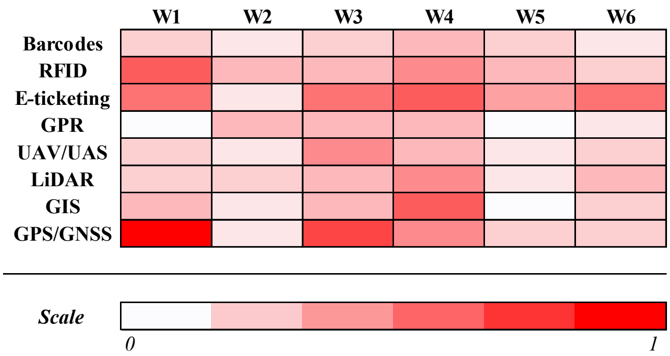
Chi-Square	DF	p-value	
0	1	1	
0	1	1	
0	2	1	
2.59	8	0.96	
10	5	**0.08**	**
3	7	0.89	
13.88	10	0.18	
11.76	10	0.31	

Figure 3. Distribution of Strengths in Asset Management and results of the Chi-Square Test for equal likelihood.

3.2. Results for Weaknesses

The distribution of weaknesses is represented by a normalized heat map as shown in Figure 5. For every technology, the darker the color of the weakness, the more that weakness was selected by respondents who used the technology. In terms of weaknesses, W2 (System Defects), W3 (Accessibility for users), W4 (Integrating with current project administration systems), and W6 (Data transfer and interoperability issues) were selected for every technology at least once. On the other hand, W1 (Loss of connectivity) and W5 (Integrating with plant/supplier IT system) were not selected for GPR, while only W5 was not selected for GIS.

The Chi-Square test for equal likelihood was significant for GPS/GNSS (p-value = 0.006, i.e., significant with 95% confidence). For GPS/GNSS, the darker intensity of W1, W3, and W4 indicates that DOTs that used the technology were more likely to face these weaknesses when compared to W2, W5, and W6.



	Chi-Square	DF	p-value	
Barcodes	1.54	5	0.91	
RFID	4.39	5	0.49	
E-ticketing	4.8	5	0.44	
GPR	1.2	3	0.75	
UAV/UAS	4.85	5	0.43	
LiDAR	3.5	5	0.62	
GIS	6.5	4	0.16	
GPS/GNSS	16.31	5	**0.006**	***

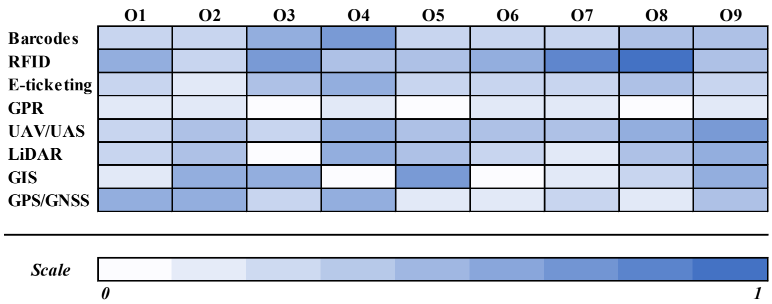
Figure 4. Distribution of Weaknesses and results of the Chi-Square Test for equal likelihood.

3.3. Results for Opportunities

The distribution of opportunities is represented by a normalized heat map as shown in Figure 6. For every technology, the darker the color of an opportunity, the more it was provided to the state DOTs through the technology. In terms of opportunities, O1 (Quality Improvement), O2 (Data Collection, Integration, and Management), O7 (Cost Reductions), and O9 (Decision-

Making Enhancement) were selected for every technology at least once. On the other hand, O3 (Tracking Capabilities) was not selected for GPR and LiDAR, O4 (Efficiency/Productivity Enhancement) was not selected for GIS, O5 (Communication Effectiveness) was not selected for GPR, O6 (Safety Enhancement) was not selected for GIS, and O8 (Schedule Acceleration) was not selected for GPR.

Moreover, the Chi-Square test for equal likelihood was not significant for any technology. This can be attributed to opportunities being realized only after technologies reach a certain level of maturity that allows DOTs to exploit most of their potential. The higher the level of maturity, the more significant certain opportunities can become.



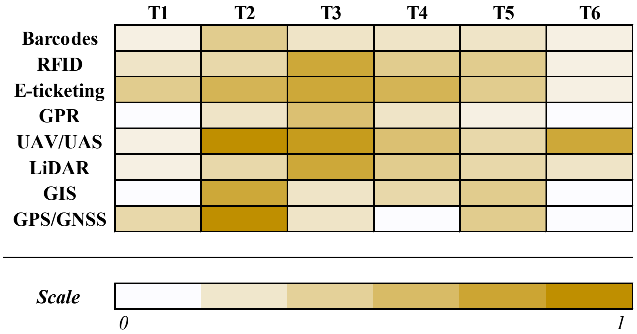
	Chi-Square	DF	p-value
Barcodes	3.44	8	0.91
RFID	5.08	8	0.75
E-ticketing	2.57	8	0.96
GPR	0	5	1
UAV/UAS	2.34	8	0.97
LiDAR	2.73	7	0.91
GIS	5.33	6	0.51
GPS/GNSS	5.82	8	0.67

Figure 5. Distribution of Opportunities and results of the Chi-Square Test for equal likelihood.

3.4. Results for Threats

The distribution of threats is represented by a normalized heat map as shown in Figure 7. For every technology, the darker the color of a threat, the more that threat was selected by respondents who used the technology. In terms of threats, T2 (Workforce skillset limitations or resistance) and T3 (Investment costs or unknown return on investment) were selected for every technology at least once. On the other hand, T1 (Resistance from third parties and vendors), T4 (Lack of needed support technology), T5 (Organization culture), and T6 (Policy/regulation restrictions) were not selected for GPR, while T1 and T6 were not selected for GIS, T4 and T6 were not selected for GPS/GNSS, and T6 was not selected for e-ticketing.

The Chi-Square test for equal likelihood was significant for GPS/SNSS (p-value = 0.09, i.e., significant with 90% confidence). The darker intensity of T2 indicates that state DOTs that used the technology were not likely to recognize these threats when compared to T1, T3, T4, T5, and T6.



	Chi-Square	DF	p-value	
Barcodes	3	5	0.69	
RFID	6.14	5	0.29	
E-ticketing	5	5	0.42	
GPR	3.6	3	0.31	
UAV/UAS	8.63	5	0.12	
LiDAR	6.4	5	0.27	
GIS	3.5	3	0.32	
GPS/GNSS	6.44	3	**0.09**	**

Figure 6. Distribution of Threats among technologies and results of the Chi-Square Test for equal likelihood.

4. Discussion

The analysis of the comprehensive SWOT framework can present a holistic view of the current status quo of the state DOTs' use of wireless and sensing technologies in highway projects as summarized in TABLE 6. This view is translated into two main forces as presented in Figure 8: the current driving forces that are pushing state DOTs to increase the use of wireless and sensing technologies, and the restraining forces that are limiting state DOTs from maximizing or exploiting the potential of these technologies in highway projects.

Starting with the driving forces, results from "strengths" and "opportunities" provide empirical evidence on the use of wireless and sensing technologies on highway projects by playing an important role in the construction phase as well as in the asset management phase. In the construction phase, technologies are allowing state DOTs to locate equipment, tools, and materials, track and document inventory, survey plots, identify underground utilities, automate equipment functionalities, conduct inspections, monitor and document project progress, and develop as-built models. In the asset management phase, the same technologies are facilitating inspection, assessing assets and their environment, identifying repair needs, and sharing information across the different departments within the state DOTs. Such use-cases of wireless and sensing technologies on highway projects – whether before, during, or after construction – are positively affecting project performance in terms of cost, schedule, safety, and quality, enhancing communication and sharing information among project stakeholders, supporting asset data management throughout the data lifecycle, and facilitating decision-making to improve processes and progress. The potential of these technologies acts as the major driver for their use, especially when state DOTs are pressured to finish complex projects under strict budgets and schedules.

Despite the major potential of wireless and sensing technologies on highway projects, state DOTs have yet to exploit or maximize this potential, and thus overcome the restricting forces. As shown in the "weaknesses" and "threats", several limitations and obstacles need to be addressed. At the technology level, technical limitations exist in terms of connectivity, data transfer, accessibility, and effects. Such limitations are natural given that technologies continue to evolve and mature for highway projects. Additionally, the nature of highway projects which extends thousands of miles crossing rural areas, rough terrains, and tough climates provides an environment that may affect the use of wireless and sensing technologies which depend heavily on signals and connectivity. In addition to these technical limitations, obstacles are also witnessed at the level of state DOTs and their scope of work. Problems such as resistance to change, labor shortage and lack of skills, high cost of capital investments, and non-supportive policies and regulations play a heavy role in hindering the use of wireless and sensing technologies.

Based on the SWOT findings and the status quo of wireless and sensing technologies in highway projects, the application of the technologies has proven to be an inviting and fertile ground for DOTs to invest in and implement. DOTs can address the restraining forces through different actions such as:

- Developing industry standards for the use of different wireless and sensing technologies whether at the state or federal level. This can help standardize the use of the technologies, explain their current applications, and provide a starting point to compare technology utilization among state DOTs and continuously improve this usage.
- Creating a task force and assigning champions who can lead the adoption of wireless and sensing technologies, and conduct virtual and in-person meetings dedicated to technologies, and allow state DOTs to understand maximize the technologies' potential. Such meetings can also be critical for sharing implementation plans, best practices, and lessons learned.
- Collaborating with the contracting community to plan and execute pilot projects that can allow DOTs, contractors, sub-contractors, and other project parties to experiment with different wireless and sensing technologies freely without consequences. Such projects allow all parties to understand the pilot technology's potential and drawbacks, draft lessons learned, and make informed decisions on whether the technology is worth rolling out.
- Collaborating with technology vendors, consultants, and research institutions. Having technology vendors available when constructing projects or conducting post-construction inspections can help vendors understand the technical issues that state DOTs face and develop solutions to solve these limitations. Consultants specialized in these technologies can also provide adequate training and conduct studies to investigate the technologies' benefits for state DOTs and return on investments. Moreover, universities and non-academic research institutions have research labs and controlled environments to test technologies and educate state DOTs on their potential and the best way to utilize them across the project lifecycle.
- Attracting, recruiting, and retaining young graduates as they can provide state DOTs with the technical skills needed to successfully implement the technology, and play an important role in promoting the technologies across departments.
- Providing middle-level and high-level leadership support can be critical to implementing the technologies and addressing resistance to change through providing resources for pilot testing, conducting training, sharing success stories, and resolving people's concerns.

5. Conclusion

This study presented a holistic investigation into the state DOTs' use of wireless and sensing technologies in highway projects. A SWOT framework was developed from previous studies, and data was gathered through a nationwide survey of subject matter experts to comprehensively understand the strengths, weaknesses, opportunities, and threats of eight technologies: barcodes, RFID, e-ticketing, GPR, UAS/UAV, LiDAR, GIS, and GPS/GNSS. Analysis of the survey shows that the technologies are used in various construction and asset management use cases, providing DOTs with multiple opportunities to improve project performance and assist project stakeholders. However, technologies do face different technical, organizational, and industry-related obstacles that limit DOTs from exploiting the technologies' maximum potential.

The findings of this study can be important for both practitioners and academicians. Practitioners can use the results to comprehensively understand the status quo of wireless and sensing technologies on highway projects. Academicians and researchers can also use the findings as a starting point to further investigate each of the technologies to maximize their use cases and address their limitations. Findings however are based on the input of subject matter experts who answered the survey. These results reflect on the eight technologies' current state of adoption and implementation, and the experts' current experience with the technologies. Such experience is expected to change as technologies continue to evolve and mature with time, and continuous input from DOTs is needed to gain a better understanding of the potential and value of wireless and sensing technologies in highway projects.

Acknowledgments

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References

[1] G. Dadi, H. Nassereddine, T. Taylor, R. Griffith, and B. Ramadan, *Technological Capabilities of Departments of Transportation for Digital Project Management and Delivery*, National Cooperative Highway Research Program Project 20-05, Synthesis Topic 52-19. Washington DC, USA: The National Academies Press, 2022. doi: 10.17226/26738.
[2] A. Ammar, H. Nassereddine, and G. Dadi, "State Departments of Transportation's Vision Toward Digital Twins: Investigation of Roadside Asset Data Management Current Practices and Future Requirements," *ISPRS Ann. Photogramm. Remote Sens. Spat. Inf. Sci.*, vol. V-4–2022, pp. 319–327, 2022, doi: 10.5194/isprs-annals-V-4-2022-319-2022.
[3] H. Nassereddine, M. B. Hatoum, G. Dadi, T. Taylor, and R. Griffith, *3D Digital Models as Highway Construction Contract Documents*, National Cooperative Highway Research Program Project 20-05, Synthesis Topic 52-14. Washington DC, USA: The National Academies Press, 2022. doi:10.17226/26683.
[4] S. Obando, "Construction techies laud $100M in infrastructure act, push for more," *Construction Dive*, 2021. https://www.constructiondive.com/news/construction-tech-praise-110-million-infrastructure-bill-push-for-more/610126/.
[5] A. Ammar, F. Maier, R. Catchings, H. Nassereddine, and G. Dadi, "Departments of Transportation Efforts to Digitize Ancillary Transportation Asset Data: A Step Toward Digital Twins," *Transp. Res. Rec.*, 2023.
[6] M. B. Hatoum, A. Ammar, H. Nassereddine, G. Dadi, A. Tripathi, and R. Sturgill, "Wireless and Sensing Technologies in U.S. Highway Projects: Usage, Maturity, Challenges, and KPIs," in *International Conference on Transportation and Development 2021*, Austin, Texas: American Society of Civil Engineers, 2023.
[7] M. B. Hatoum, A. Tripathi, A. Ammar, H. Nassereddine, G. Dadi, and R. Sturgill, "Investigating the Maturity and Implementation of Wireless and Sensing Technology in Highway Construction and Infrastructure Asset Management," in *Proceedings of the Civil Engineering Annual Conference 2023*, Moncton, NB, Canada: Canadian Society of Civil Engineers, 2023.
[8] M. B. Hatoum, H. Nassereddine, and G. Dadi, "Factors Influencing the Adoption of Construction 4.0 Technologies by Departments of Transportation," in *International Conference on Transportation and Development (ICTD 2023)*, Austin, Texas: American Society of Civil Engineers, 2023.
[9] A. Tripathi, H. Nassereddine, G. Dadi, and R. E. Sturgill, "Toward a Readiness Assessment for Wireless Technologies for Highway Construction and Infrastructure Asset Management," in *Construction Research Congress 2022*, Arlington, Virginia, 2022, pp. 125–134. doi: 10.1061/9780784483961.014.
[10] G. B. Dadi *et al.*, *Guidelines for Applications of RFID and Wireless Technologies in Highway Construction and Asset Management.* in Research Project, no. Project 03-140. Washington, DC , USA: National Cooperative Highway Research Program, 2023. [Online]. Available: https://trid.trb.org/View/1628592
[11] E. Gurel and M. Tat, "SWOT Analysis: A Theoretical Review," *J. Int. Soc. Res.*, vol. 10, no. 51, pp. 994–1006, 2017, doi: http://dx.doi.org/10.17719/jisr.2017.1832.
[12] K. Zima, E. Plebankiewicz, and D. Wieczorek, "A SWOT Analysis of the Use of BIM Technology in the Polish Construction Industry," *Buildings*, vol. 10, no. 1, 2020, doi: 10.3390/buildings10010016.
[13] C. Namugenyi, S. L. Nimmagadda, and T. Reiners, "Design of a SWOT Analysis Model and its Evaluation in Diverse Digital Business Ecosystem Contexts," *Procedia Comput. Sci.*, vol. 159, pp. 1145–1154, 2019, doi: 10.1016/j.procs.2019.09.283.
[14] A. Nigussie, "Application of SWOT Analysis in Construction Projects," 2021, doi: 10.1080/02615470020028364.
[15] J. C. Gontier, P. S. P. Wong, and P. Teo, "Towards the Implementation of Immersive Technology in Construction – a SWOT Analysis," *J. Inf. Technol. Constr. ITcon*, vol. 26, pp. 366–380, 2021, doi: https://doi.org/10.36680/j.itcon.2021.020.
[16] D. Yao and B. G. de Soto, "A preliminary SWOT evaluation for the applications of ML to Cyber Risk Analysis in the Construction Industry," *IOP Conf. Ser. Mater. Sci. Eng.*, vol. 1218, no. 1, p. 012017, Jan. 2022, doi: 10.1088/1757-899x/1218/1/012017.
[17] H. S. E. Mohammed and W. J. S. Alharthi, "Blockchain Technology and the Future of Construction Industry in the Arab Region: Applications, Challenges, and Future Opportunities," *Eng. Res. J.*, vol. 173, no. 0, pp. 411–441, 2022, doi: 10.21608/erj.2022.223618.
[18] A. Tezel, E. Papadonikolaki, I. Yitmen, and P. Hilletofth, "Preparing construction supply chains for blockchain technology: An investigation of its potential and future directions," *Front. Eng. Manag.*, vol. 7, no. 4, pp. 547–563, Dec. 2020, doi: 10.1007/s42524-020-0110-8.
[19] S. A. Ismail, S. Bandi, and Z. N. Maaz, "An Appraisal into the Potential Application of Big Data in the Construction Industry," *Int. J. Built Environ. Sustain.*, vol. 5, no. 2, May 2018, doi: 10.11113/ijbes.v5.n2.274.
[20] G. Ozcan-Deniz, "Expanding Applications of Virtual Reality in Construction Industry: A Multiple Case Study Approach," *J. Constr. Eng. Manag. Innov.*, vol. 2, no. 2, pp. 48–66, 2019, doi: 10.31462/jcemi.2019.02048066.
[21] D. Tran, C. Harper, and R. Sturgill, "Highway Infrastructure Inspection Practices for the Digital Age," Transportation Research Board, Washington, DC, NCHRP Project 20-05, Topic 52-01, 2022. [Online]. doi: 10.17226/26592

OPTIONS OF AUTOMATED SURVEYS FOR MAINTENANCE MONITORING SERVICES OF HERITAGE BUILDINGS

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Abstract

Maintenance monitoring is a key factor in the economic preservation of heritage buildings. Maintenance monitoring services are supporting the responsible staff in their preservation tasks and keeping the heritage buildings and sites continuously in a proper condition. Regular monitoring is an important, but time-consuming activity which needs a relevant amount of human workhour to be conducted properly. Automated survey methods are developed worldwide, to help the work of various professional research staff to investigate the state of different structures of the heritage buildings, however, these automated surveys are usually executed individually, not as integrated parts of the maintenance management systems. In this paper, the options of automation methods are analyzed regarding the various regular tasks of the monitoring staff, and suggestions are made to reduce human activities and to support the monitoring staff with fixed IoT and/or mobile (robotic) survey units at the maintenance monitoring service activities.

Peer-review under responsibility of the scientific committee of the Creative Construction Conference 2023.

Keywords: automated monitoring, building preservation service, heritage maintenance, IoT units.

1. Introduction

Monument sentinel services are applied on many heritage sites [1] in the Netherlands (Monumentenwacht Nederland), Belgium (Monumentenwacht Vlaanderen), and Denmark (Bygningsbevaring), in the frame of which the maintenance monitoring of the heritage site is performed by a crew, who are trained in on-site diagnostics.

Generally, it means one to four site visits each year by a professional staff, who are inspecting, and monitoring the actual state of the building, conducting minor on-site preservation/conservation actions, and envisage larger restoration tasks if the building's actual state would require it.

In the last few decades, there were a lot of attempts for automatization of many kinds of inspection, that could make the work of the sentinel services easier and more effective. With the help of contemporary technologies, the way of inspections could be changed.

There are many attempts for conducting different kinds of inspections or monitoring tasks automated on a heritage site. The application of IoT-s became quite common in the field of remote monitoring worldwide. Various network-based sensor systems are developed and tested adopting site characteristics and various problem maps, which were completed by the application of machine learning techniques in some cases as well.

In this study, an investigation is made to analyse the options of automated methods for a continuous survey.

2. Methodology

In this paper, the options of using digital network-based tools (IoT-s) for the maintenance monitoring of heritage buildings and sites are discussed. These tools can be a great help for the staff of the sentinel service and can collect much information for daily use, and conservation plans.

In the first part of the paper some already applied systems, and methods are introduced. In the second part, the needs of the surveys in the case of a monument sentinel service system are analyzed. Finally, in the third part, an attempt is made to evaluate the overlapping of the two in order to detect the need for further developments.

3. Digital monitoring of heritage sites

The application of digital sensing techniques and IoT-s for monitoring heritage buildings and sites become more and more important in the present day. We can observe a continuous development and spread of the methods. Regarding the applied digital tools (IoT-s, sensors), and systems (WSN-s) three somewhat overlapping categories with no clear boundaries can be distinguished: the digital imaging methods of the artefacts, the structural health monitoring and the monitoring of the environmental characteristics which are demonstrated in *sections 3.1, 3.2 and 3.3* respectively. Finally, in *section 3.4* network development options and some research with mobile survey units are discussed.

3.1. Digital imaging methods

Among imaging methods, there are many techniques most of which can be considered close-range techniques [2], as far as the sensing instruments have to be used in proximity to the investigated artefacts or objects. Close-range sensing technologies are the photogrammetric techniques, laser scanning techniques, like terrestrial laser scanning (TLS) or light detection and ranging (LiDAR), infrared thermography (IRT), multispectral imaging, ultrasonic sensing or ground-penetrating radar that is frequently used for example at archaeological surveys. [2]

Digital imaging methods are mostly used to get visual information, for some kind of documentation or image-based data recordings, however structural health monitoring or environmental surveys can be based on it too.

3.2. Structural health monitoring

In the case of structural health monitoring as well several methods are used for the monitoring of various impacts [3], the most frequent of which are seismic effects [4, 5], dynamic effects like traffic or noise [7] and those consequences like crack building or displacements [6, 7, 8].

From the above-mentioned techniques 3D Laser scanning can be applied for an overall assessment of the morphological changes of the outer surfaces and global navigation satellite systems (GNSS) can be applied for fast and more frequent 3D monitoring [9].

For monitoring structural cracks, for instance, Hall sensors [6] active thermography, or ultrasonic methods can be applied [7].

In the case of structural health monitoring machine learning techniques can be applied e.g. for surface damage detection, predictions about ageing or for the preparation of preventive actions like removing dust, fungi or deposits. [10, 11].

3.3. Environmental monitoring

The monitoring of environmental characteristics is applied for a long time now for instance in the case of closed museum spaces, among which temperature and relative air humidity are the most frequently measured ones [12, 13], but air quality and atmospheric pressure can be monitored as well [12, 14, 15]. There are also some attempts for matching the environmental data with visual phenomena like efflorescence [13, 16].

For obtaining quantitative data to measure water content in heritage masonry structures, nuclear magnetic resonance (NMR) or microwave-based integrated sensors for performing humidity and salinity measurements can be used [17, 18]. Machine learning techniques were also applied in some cases lately. An example of that is the research made by Hoła and Sadowski [19] for non-destructive in situ identification of the moisture content.

3.4. The monitoring networks - remote monitoring – monitoring robots

There are several studies for the continuous tracking of environmental parameters, with the help of wireless sensor networks (WSN) [6,12, 20, 21, 22, 23, 24] as well as for the work of self-adapting IoT sensing for built heritage [25]. For the communication of the nodes in the system Bluetooth, WiFi, Zigbee, or LoRa technologies are used most frequently [12, 26, 27].

Apart from the fixed IoT-s (*Figure 1a*) in some cases monitoring robots can be used (*Figure 1b*) for survey tasks. In these fields, there are also a few known research projects. The Irma3D (Intelligent Robot for Mapping Application in 3D) project was performed by the University of Würzburg and Jacobs University Bremen [28], a LiDAR-equipped robot was developed by the Department of Geological Engineering of the Missouri University of Science and Technology [28], car mounted sensors were applied for air-quality monitoring as well [15], and a modest study was also made in our former research [29].

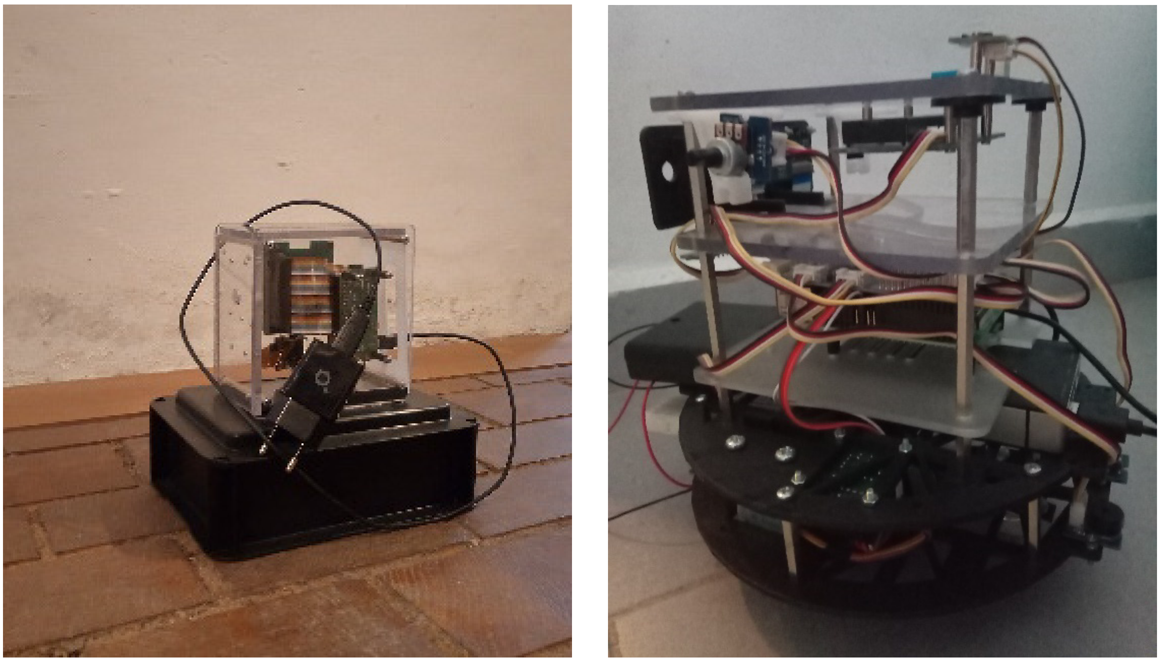

Fig. 1. (a) fixed survey unit; (b) mobile survey unit

4. Discussion

In the case of heritage monitoring the phenomena are normally very complex and in the case of collecting information on the state of historic sites and buildings, typically, many aspects have to be observed and many observation locations are needed for collecting the proper amount and quality of information for the required preservation and conservation actions on the heritage site.

The goal of this paper is to investigate the opportunities of using the known methods in a system for monument sentinel services for continuous observation and monitoring purposes at heritage sites. *Table 1* summarises the used technologies according to the application fields.

Table 1. Digital tools for monitoring heritage buildings and sites

Field of observation	***Applied sensor/technology***	***Applied techniques based on artificial intelligence (AI)***
Temperature and air humidity	digital temperature sensor (DT), digital humidity and temperature sensors (DHT), complex sensors	
Barometric pressure	barometric pressure sensor, or complex sensor	
Moisture in the structure	analogue and capacitive moisture sensors, thermal camera, nuclear magnetic resonance, microwave-based integrated sensors	machine learning can be used for in-situ identification of the moisture content
Efflorescence	camera, salinity measurement sensors	machine learning can be used for predictions about the state
Crack buildings	Hall sensor, camera, thermal camera, ultrasonic sensors	machine learning can be used for surface damage detection or predictions about ageing
Dislodgment of elements	camera, photoelectric sensors	
Deterioration (biotic, abiotic),	camera	machine learning can be used for predictions about the state, fungi, deposits
Air quality	gas sensors (CO, CO_2, volatile organic compounds, alcohol, etc.)	
Corrosion	camera	machine learning can be used for predictions about the state

As far as heritage sites are unique regarding their age and history – as a consequence of their problem map, – the site characteristics have a very important role in the configuration of the system to be applied on the site. The typical fields of investigation of a heritage site are demonstrated in *Table 2.*

In *Table 3* there is a summary of the options for the application of digital sensors, and survey systems in the case of heritage sites, considering the same fields of investigation and tasks (survey categories) which were listed in *Table 2.*

In the case of on-site monitoring on heritage sites, there are further fields of investigations, which are not related to building structures, however, can be supported by automated inspection technologies. *Table 4* demonstrates these fields.

Artificial Intelligence can be used e.g. for object detection methods for recognizing problems, deterioration or neglected states at an early phase, not just for structural health monitoring, but also for detection of such problems as jamming in gutters, debris in roof valleys or penetration of water etc.

A challenging problem in the field of automated monitoring is that fixed survey units have a limited range of monitoring on the one hand, and their capacity is not used fully by their measuring tasks on the other. This problem could be solved by automated mobile units, which according to the monitoring needs of the site are able to turn into various directions and move in a defined route. These units could replace a couple of similar nodes in an area of the heritage site.

A further challenge is that the available fully functioning robots are rather expensive, and their knowledge usually exceeds the level of the required tasks, for which reason the development of simpler robots would be reasonable. 10-20 sensors which are optimized for the required survey tasks would be enough for the monitoring units which is not much more than what the popular robotic vacuum cleaners have. This option was already tested in some projects [15, 28, 29], however, further research could be conducted in this field.

Table 2. Fields of investigation related to the building structures applied by a heritage sentinel system

Category	*Structure*	*Inspection tasks*
timber structures	carpenter structures	visual soundness inspection, deterioration detection, timber decay analyses
	timber stairs	
	doors and windows, frames and sashes	
	furniture	
	timber railings	
roof covering, flashings	shingles	visual soundness inspection, dislodgement inspection
	roof tiles	
	slate	
	sheet metal roofs, flashings	visual soundness inspection, corrosion inspection
solid load-bearing structures	foundations	visual soundness inspection, crack detections,
	walls, pillars	
	beams, slabs	
metal elements (wrought iron, steel, cast iron, copper, bronze etc.)	grills, railings	visual soundness inspection, corrosion detection
	metal structural elements	
	elements of building services (e.g. heating units)	
	elements of building electric systems (e.g. lamps)	
stone, ceramic pavements and claddings	ceramic tiling (wall/floor)	visual soundness inspection, deterioration, moisture
	stone/brick paving	
	stone/brick facade	
	artificial stone, cement plates	
timber surfaces	wainscotting	visual soundness inspection, deterioration detection, timber decay analyses
	timber facades	
	timber floors	
rendered, plastered surfaces, pointing	joints, pointing	visual soundness inspection, crack detection, moisture/salt detection
	plaster, stucco	
glass artefacts, glazing	window glazing (simple or stained glass)	visual inspection

The challenge with WSN systems is to find the proper network technology or combination of technologies, that serves well the tasks of the system in case of the given circumstances on the sites. Many heritage sites have a certain distance from central urban areas where the mobile network might not be appropriate for the communication of the monitoring units with the internet, and many structural elements of the heritage sites could be a hampering factor regarding the communication of the monitoring nodes. In many cases even a proper electric supply system is problematic.

Regarding the WSN, if the mobile network signal is high, and the power supply is given, we can apply WiFi-based systems, but if we need an individual power supply, or the network signal strength is low, then other solutions like e.g. LoRa (long-range) technology should be considered.

Table 3. Matching the requirements of a monument sentinel system with the existing digital options

Category	***Structure***	***Sensors, measuring methods***
timber structures	carpenter structures	camera, heat camera, moisture sensors, environmental sensors
	timber stairs	
	doors and windows, frames and sashes	
	furniture	
	timber railings	
roof covering, flashings	shingles	camera
	roof tiles	
	slate	
	sheet metal works, flashings	
solid load-bearing structures	foundations	Hall sensor, active thermography, ultrasonic sensors
	walls, pillars	
	beams, slabs	
metal elements (wrought iron, steel, cast iron, copper, bronze etc.)	grills, railings	camera, ultrasonic methods
	metal structural elements	
	elements of building services (e.g. heating units)	
	elements of building electric systems (e.g. lamps)	
stone, ceramic pavements and claddings	ceramic tiling (wall/floor)	camera, thermal camera, moisture sensors
	stone, brick paving	
	stone, brick facade	
	artificial stone, cement plates	
timber surfaces	wainscotting	camera, thermal camera, moisture sensors
	timber facades	
	timber floors	
rendered, plastered surfaces, pointing	joints, pointing	camera, dislodgement sensors (Hall, ultrasonic, moisture sensors)
	plaster, stucco	
glass artefacts, glazing	window glazing (simple or stained glass)	camera

Table 4. Further fields of investigation applied by a monument sentinel system

Field of observation	***Place/target of observation***	***Sensor type or method***
Cleanness of surfaces	routs, sidewalks, wall surfaces	camera
Unhampered working of systems	rainwater goods, gutter, lighting system, heating pipes	camera, thermal camera, built-in sensors
Vegetation around the house	risk for deterioration, unpleasant impact	camera, thermal camera

On the bases of our own experiences and the experiences of other projects mentioned in *section 3*, we can state that automated monitoring is a great option on heritage sites, and WSN systems are adequate tools to organize the individual units into a well-functioning system.

Summary

In summary, it can be stated, that there have been already many attempts made to monitor the state or the various environmental impacts of a heritage building. Most territory of need is covered with technology, and as well many digital networks were already used on heritage sites. A system that serves directly the need of a sentinel system can be developed, and guidelines for a digital controlling system can be established shortly.

References

[1] Wu, Meiping, and Birgit van Laar. "The Monumentenwacht model for preventive conservation of built heritage: A case study of Monumentenwacht Vlaanderen in Belgium." *Frontiers of Architectural Research* 10.1 (2021): 92-107. doi: 10.1016/j.foar.2020.07.007
[2] Adamopoulos, Efstathios, and Fulvio Rinaudo. "Close-range sensing and data fusion for built heritage inspection and monitoring—a review." Remote Sensing 13.19 (2021): 3936. doi: 10.3390/rs13193936
[3] Gopinath, Vinoth Kanna, and Ravi Ramadoss. "Review on structural health monitoring for restoration of heritage buildings." Materials Today: Proceedings 43 (2021): 1534-1538. doi: 10.1016/j.matpr.2020.09.318
[4] Campostrini, Gian Paolo, et al. "A Bayesian approach to rapid seismic vulnerability assessment at urban scale." *International Journal of Architectural Heritage* 12.1 (2018): 36-46. doi: 10.1080/15583058.2017.1370506
[5] Potenza, Francesco, et al. "Long-term structural monitoring of the damaged Basilica S. Maria di Collemaggio through a low-cost wireless sensor network." *Journal of Civil Structural Health Monitoring* 5 (2015): 655-676. doi: 10.1007/s13349-015-0146-3
[6] Addabbo, Tommaso, et al. "A city-scale IoT architecture for monumental structures monitoring." Measurement 131 (2019): 349-357. doi: 10.1016/j.measurement.2018.08.058
[7] Maierhofer, Christiane, et al. "Monitoring of cracks in historic concrete structures using optical, thermal and acoustical methods." *Built Heritage: Monitoring Conservation Management* (2015): 93-102. doi: 10.1007/978-3-319-08533-3_8
[8] Lima, Hugo F., et al. "Structural health monitoring of the church of Santa Casa da Misericórdia of Aveiro using FBG sensors." *IEEE Sensors Journal* 8.7 (2008): 1236-1242. doi: 10.1109/JSEN.2008.926177
[9] Pereira, Telmo Dias, and Diogo Mateus. "Monitoring Noise and Vibration in Santa Clara-a-Velha Monastery." *Built Heritage: Monitoring Conservation Management*. Cham: Springer International Publishing, 2014. 103-112. doi: 10.1007/978-3-319-08533-3_9
[10] Mishra, Mayank. "Machine learning techniques for structural health monitoring of heritage buildings: A state-of-the-art review and case studies." Journal of Cultural Heritage 47 (2021): 227-245. doi: 10.1016/j.culher.2020.09.005
[11] Fiorucci, Marco, et al. "Machine learning for cultural heritage: A survey." Pattern Recognition Letters 133 (2020): 102-108. doi: 10.1016/j.patrec.2020.02.017
[12] Klein, Levente J., et al. "Wireless sensor platform for cultural heritage monitoring and modelling system." *Sensors* 17.9 (2017): 1998. doi: 10.3390/s17091998
[13] Vidovszky, István és Pintér, Farkas (2021) *Development of IoT-based condition survey units to monitor salt damages on plastered and rendered surfaces.* ARCHEOMETRIAI MŰHELY, 18 (1). pp. 45-53. ISSN 1786-271X doi: 10.55023/issn.1786-271X.2021-003
[14] Patkó, Csilla, István Patkó, and Zoltán Pásztory. "Indoor air quality testing in low-energy wooden houses: Measurement of formaldehyde and VOC-s." *Acta Polytech. Hung* 10 (2013): 105-116. doi:
[15] Völgyesi, Péter, et al. "Air quality monitoring with sensormap." *2008 International Conference on Information Processing in Sensor Networks (ipsn 2008)*. IEEE, 2008. doi:10.1109/IPSN.2008.50
[16] K. Zehnder, O. Schoch, "Efflorescence of mirabilite, epsomite and gypsum traced by automated monitoring on-site", Journal of Cultural Heritage 10 (2009) 319–330. doi: 10.1016/j.culher.2008.10.009
[17] Furini, Alessio, et al. "Integrated measurement techniques for the monitoring of the ancient walls of Ferrara." *Built Heritage: Monitoring Conservation Management* (2015): 155-164. doi: 10.1007/978-3-319-08533-3_13
[18] Proietti, Noemi, et al. "MOdihMA at Sforza Castle in Milano: Innovative techniques for moisture detection in historical masonry." *Built Heritage: Monitoring Conservation Management*. Cham: Springer International Publishing, 2014. 187-197. doi: 10.1007/978-3-319-08533-3_16
[19] Hoła, Anna, and Łukasz Sadowski. "Non-destructive in situ identification of the moisture content in saline brick walls using artificial neural networks." Creative Construction Conference 2019. Budapest University of Technology and Economics, 2019. doi: 10.3311/CCC2019-012
[20] D'Amato, Fabrizio, Paolo Gamba, and Emanuele Goldoni. "Monitoring heritage buildings and artworks with wireless sensor networks." 2012 IEEE Workshop on Environmental Energy and Structural Monitoring Systems (EESMS). IEEE, 2012. doi: 10.1109/EESMS.2012.6348392

[21] Ceriotti, Matteo, et al. "Monitoring heritage buildings with wireless sensor networks: The Torre Aquila deployment." 2009 International Conference on Information Processing in Sensor Networks. IEEE, 2009. doi: 10.1145/1602165.1602191

[22] Anastasi, Giuseppe, Giuseppe Lo Re, and Marco Ortolani. "WSNs for structural health monitoring of historical buildings." *2009 2nd Conference on Human System Interactions*. IEEE, 2009. doi: 10.1109/HSI.2009.5091041

[23] S. Madakam, R. Ramaswamy, S. Tripathi, “Internet of Things (IoT): A Literature Review. Journal of Computer and Communications”, 3 (2015) 164-173. doi: 10.4236/jcc.2015.35021

[24] S. Bruno, M. De Fino, F. Fatiguso, “Historic Building Information Modelling: performance assessment for diagnosis-aided information modelling and management,” Automation in Construction 86 (2018) 256–276 doi:10.1016/j.autcon.2017.11.009

[25] Tse, Rita, et al. "Self-adaptive Sensing IoT Platform for Conserving Historic Buildings and Collections in Museums." *IoTBDS*. 2020. https://www.scitepress.org/Papers/2020/94702/94702.pdf, doi: 10.5220/0009470203920398

[26] Mesas-Carrascosa, Francisco Javier, et al. "Monitoring heritage buildings with open source hardware sensors: A case study of the mosque-cathedral of Córdoba." Sensors 16.10 (2016): 1620. doi: 10.3390/s16101620

[27] A. Perles, E. Pérez-Marín, R. Mercado, J. D. Segrelles, I. Blanquer, M. Zarzo, F. J. Garcia-Diego, “An energy-efficient internet of things (IoT) architecture for preventive conservation of cultural heritage,” Future Generation Computer Systems 81 (2018) 566–581. doi: 10.1016/j.future.2017.06.030

[28] Bock, Thomas, and Thomas Linner. Construction robots: Volume 3: Elementary technologies and single-task construction robots. Cambridge University Press, 2016. doi: 10.1017/CBO9781139872041

[29] Vidovszky, I., and F. Pintér. "IoT System for Maintenance Monitoring of Historic Buildings–Smart Monitoring." *IOP Conference Series: Materials Science and Engineering*. Vol. 1218. No. 1. IOP Publishing, 2022. doi: 10.1088/1757-899X/1218/1/012007

SIMULATION-BASED OPTIMIZATION OF PATH PLANNING FOR CAMERA-EQUIPPED UAV CONSIDERING CONSTRUCTION ACTIVITIES

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Abstract

Automated progress monitoring of construction sites using cameras has been proposed in recent years. However, collecting images or videos using fixed or pan-tilt-zoom cameras is still limited by the inability to adapt to the dynamic construction environment. Therefore, considerable attention has been paid to using camera-equipped unmanned aerial vehicles (CE-UAVs), which provide mobility to the camera over the construction site. Previous studies in this area proposed methods for capturing the as-built BIM model by using structure from motion (SFM). However, data collection of construction activities of workers and equipment using CE-UAVs has not been discussed before. This paper proposes a method to perform simulation-based optimization of path planning for CE-UAVs to allow automated and effective data collection of construction activities based on a high 4D-LOD as-planned BIM, which includes a detailed micro-schedule and the corresponding workspaces. This method can identify the most informative views of the workspaces and the optimal path for data capturing. The proposed method considers the following requirements and constraints: (1) The fields of view should be optimized to cover the areas of interest and to ensure visibility of the targets considering occlusions according to the 4D BIM model; (2) The path of the UAV should be optimized to allow the data collection from multiple dynamic targets over a large construction site considering the location of activities on the site at specific times and their importance level while reducing the travel cost; and (3) The data collection should consider the requirements for computer vision processes. A case study is developed to demonstrate the feasibility of the proposed method.

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Keywords: Construction activity; Data collection; Path planning; 4D BIM; UAV.

1. Introduction

Construction projects generate a massive amount of data. Among the different sources of construction data, videos/images collected from construction sites can have a great impact on improving construction management [1]. With the emergence of advanced computer vision (CV) techniques, it is now possible to extract rich semantics and detailed information from images, enabling more comprehensive analysis in construction management. However, collecting videos using fixed or pan-tilt-zoom cameras is limited by the site geometry and the inability to adapt to the dynamic construction environment. Although previous studies tried to identify the most informative views of cameras according to 4D BIM to optimize the installation plan [2– 5], the problems related to the dynamic construction environment cannot be completely resolved. For instance, it is difficult to guarantee a high quality of the video and full coverage of the area at a reasonable installation cost. Furthermore, the coverage is affected by occlusions due to the changes of site geometry or temporal occupancy of the site.

To overcome such limitations, considerable attention has been paid to automated video collection using camera-equipped unmanned aerial vehicles (CE-UAVs), which provide mobility to the camera to fit its field of view automatically to the important parts of the construction site while avoiding occlusions [6–8]. At the time being, the research related to path planning for optimizing video collection by CE-UAV is limited to the scanning of static objects on construction sites in both outdoor [9, 10] and indoor environments [11]. These methods aim to optimize the path to meet the requirements of data processing for 3D reconstruction and inspection, including the visibility and avoidance of occlusions, the field of view, the overlap rate, the orientations, the object resolution in the images, etc. Although the schedule is considered for the generation of data collection paths in different construction phases [9], the environment during the flight operation is assumed to be static.

This paper proposes a method to perform simulation-based optimization of path planning for CE-UAVs to allow automated and effective data collection of construction activities based on a high 4D-LOD as-planned BIM, which includes a detailed micro-schedule and the corresponding workspaces. In addition, a case study is developed to demonstrate the feasibility of the proposed method.

2. Proposed Method

In general, the data collection of dynamic objects using CE-UAVs has the following requirements and constraints during the operation: (1) The fields of view should be optimized to cover the areas of interest and to ensure visibility of the targets considering occlusions according to the 4D BIM model; (2) The path of the UAV should be optimized to allow the data collection from multiple dynamic targets over a large construction site considering the location of activities on the site at specific times and their importance level while reducing the travel cost; and (3) The data collection should consider the requirements for computer vision processes (e.g., the distance to the target to ensure high resolutions, the angle of the camera, stable field of view, etc.). In this study, a method is proposed to consider the mentioned requirements and optimize the path for CEUAVs to perform hovering at the best viewpoints (VPs) to collect data about workers and equipment in different workspaces considering the micro-schedule. As one of the requirements of CV-based activity recognition methods, videos with a stable field of view are preferable in order to obtain better results regarding the accuracy and processing efficiency. As such, in this research, only the videos that are captured when the UAV is hovering are considered useful for further processing. The proposed method consists of three modules, as shown in Figure 1: (1) Preparation of simulation platform; (2) Identification of the top-ranking VPs of the 4D workspace; and (3) Path planning for the UAV to minimize the travel cost.

In the first module, for example, as shown in Figure 2(a), three 4D workspaces (A, B, C) are identified from the 4D BIM. A is the workspace for work package WP_A, which is active during $t_1 – t_4$; B is for WP_B during $t_1 – t_3$; and C is for WP_C during $t_2 – t_4$. The top view of the corresponding workspaces in different durations is shown in Figure 2(b). The solution variables for the VPs optimization module are then identified for the generation of search space according to the 4D workspaces. In this method, the position of the camera (x, y, z), yaw angle of the UAV (φ), and the tilt angle of the camera (θ) are considered. At last, cubic cells are generated within the workspaces to prepare the simulation environment for calculating the camera coverage of workspaces using the method proposed by Albahri and Hammad [12]. Importance values (IV) are assigned to the cells considering the location (whether the cell is near the products), and the importance level and priority of the associated task.

In the second module, with the workspaces and search spaces of each work package in known durations, the top-ranking VPs, where the hovering camera can have good coverage of the workspace, are selected using a genetic algorithm (GA).

In the third module, the generalized traveling salesman problem (GTSP) is solved using another GA to find the minimum-cost path [13] to allow the CE-UAV to collect videos from one of the top-ranking VPs of each workspace. The GTSP is a NP-hard problem and a variation of traveling salesman problem (TSP), which aims to find the optimal Hamiltonian tour passing through one node from each cluster of nodes. In the above example, from t_1 to t_2, workspaces A and B are active. Multiple top-ranking VPs are identified in their corresponding search spaces (e.g., a for workspace A, b for workspace B). Then, using the GA to solve the

GTSP, a^* and b^* are selected as the best VPs to generate the path with the lowest travel cost. For the duration t_2 to t_3 and t_3 to t_4, similar steps are followed to select the top-ranking VPs and to generate the optimal paths. The cycle path duration is determined based on the expected data-capturing frequency and the number of cycles that will occur within the maximum operation duration, which is limited by the UAV battery. Then, the hovering duration at each VP in one cycle is calculated considering the coverage of workspaces at different VPs and the corresponding importance level of the task. At last, the cycle path coverage is calculated to validate the generated path is efficient and has good coverage of the workspaces.

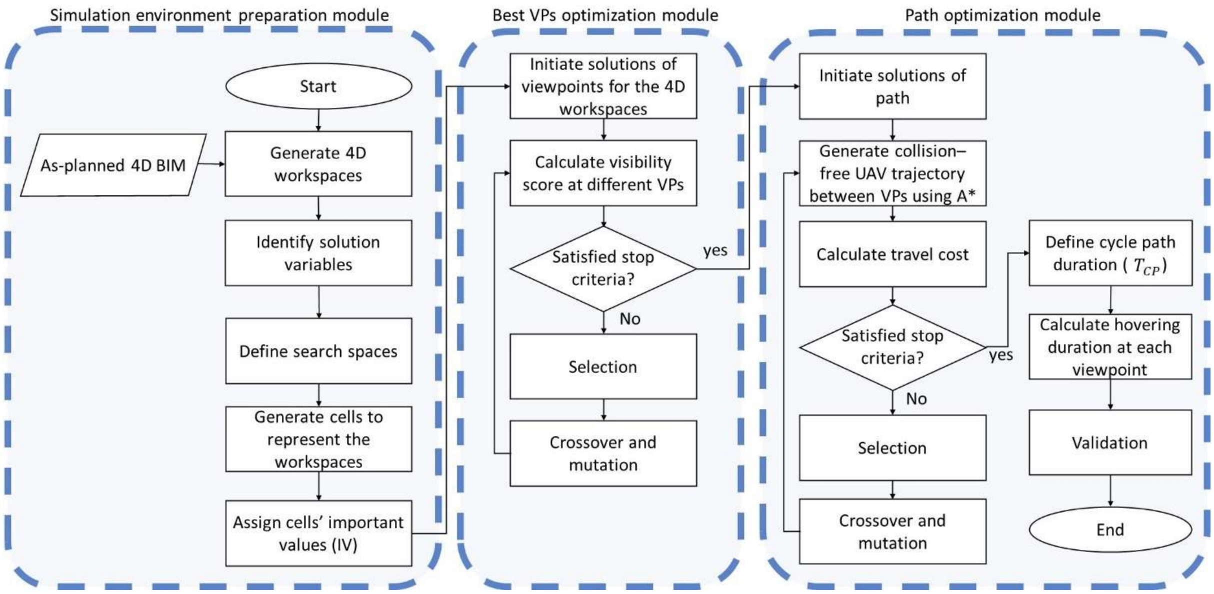
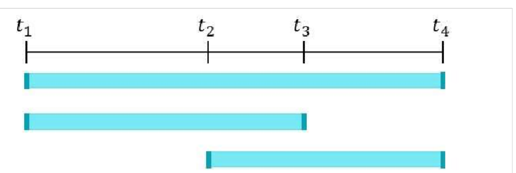
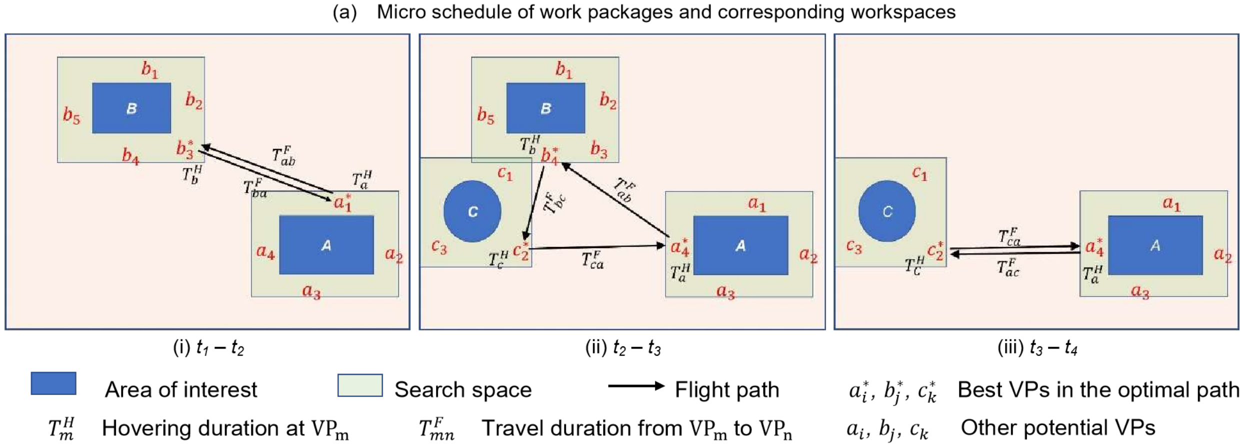


Figure 1 Proposed method

Work package	Workspace	Duration
WP_A	A	$t_1 - t_4$
WP_B	B	$t_1 - t_3$
WP_C	C	$t_2 - t_4$



(a) Micro schedule of work packages and corresponding workspaces



(b) UAV path in different duration

Figure 2 Example of path planning for CE-UAV considering activities on the construction site

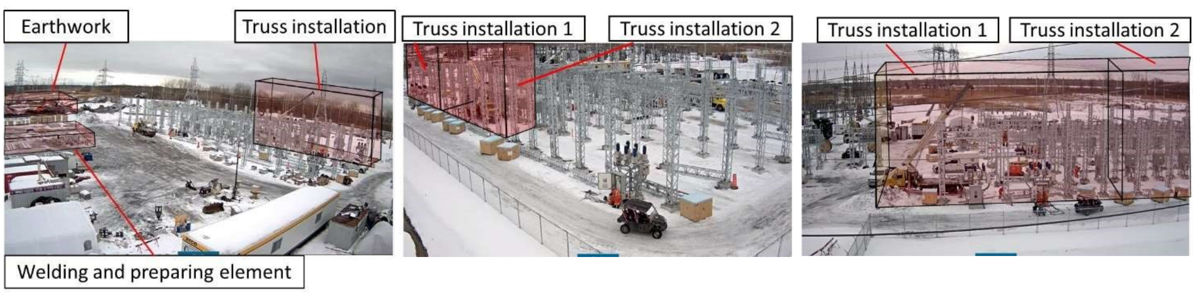
3. Implementation and Case Study

3.1 Implementation

A prototype system was developed using Unity3D [14] and Python [15]. The BIM model was imported into
Unity3D to create a simulation platform for calculating visibility scores using the Raycast function that detects occlusions between the VPs and the generated cells, and for determining optimal paths between two VPs using a A* 3D pathfinding function. The evolutionary optimization processes were performed using the opensource PYGAD library in Python [16]. Communication between Unity3D (client) and Python (server) was facilitated using the Transmission Control Protocol/Internet Protocol (TCP/IP).

3.2 Case study

A case study is conducted to validate the applicability of the proposed method and the developed prototype system. The case study is developed based on the construction activities during one whole day on the construction site of an electric substation. Figure 3 shows the images of the site collected from three fixed cameras. The schedule for the construction activities on this day was manually generated based on the videos collected from the fixed cameras, as shown in Figure 4. It is important to note that the task of truss installation was split into two separate work packages due to the crane's relocation, resulting in different workspaces. By combining the 3D BIM and the schedule, a 4D BIM was generated and used as the input for Unity3D. Workspaces at different durations were then created as explained in Section 2. Cells were generated with a uniform dimension of 1 m x 1 m x 1 m.



(a) Camera 1 (b) Camera 2 (c) Camera 3

Figure 3 Construction site and micro-tasks

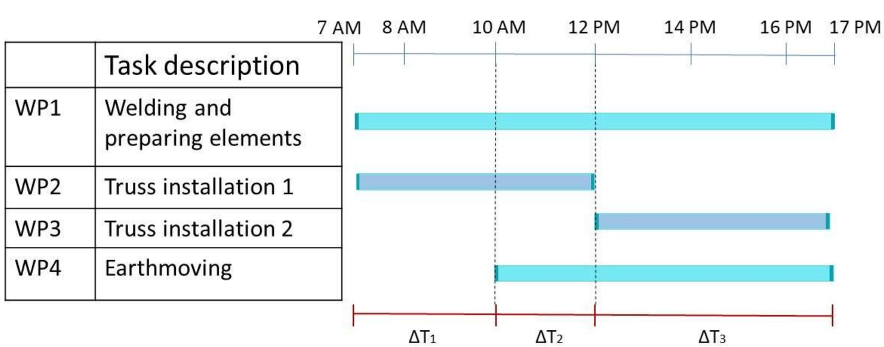


Figure 4 Micro schedule of the tasks

The UAV used in the case study is assumed to be DJI Matrice 100 using a TB48D battery, which could ascend at a maximum speed of 5 m/s, descend at a maximum speed of 4 m/s, and reach a top speed of 17 m/s in GPS mode. Therefore, the time the UAV takes to travel between two points at different heights will vary. The only payload carried by the UAV is assumed to be the Zenmuse X3 4K camera, with a diagonal FOV of 94° (vertical FOV of about 62° and horizontal FOV of about 84°), weighing 221 g. According to [17], this payload allows for an approximate flight time of 24 minutes. It is assumed that 10 cycles are preferable for the operation with a full-charged battery. As such, the cycle path time for the UAV was set to 2 minutes in the case study.

In the GA used to identify the top-ranking VPs, the number of generations is set at 50, with a population size of 500. The algorithm employs a two-point crossover with a probability of 80% and a random mutation probability of 5%. On the other hand, the GA for GTSP also uses 100 generations but with a smaller population of 200 due to the smaller search space. It employs a single-point crossover with a probability of 80% and the same random mutation probability of 5%.

3.3 Results

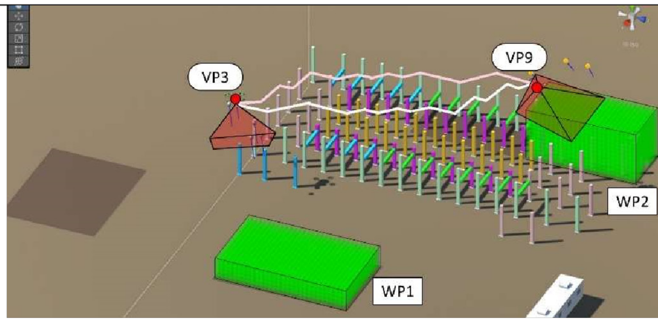
Table 1 lists the best five VPs for each workspace as the results from the VPs optimization module, along with their position, orientation, and corresponding visual coverage of the workspace. For the truss installation, the coverage at each of the top-ranking VPs exceeds 90%, indicating a high level of visibility. On the other hand, for the earthmoving workspace and the workshop, where there are no obstructions, the visual coverage at the identified VPs is 100%. These results demonstrate the effectiveness of the selected VPs in providing high coverage of the respective workspaces.

Table 1 Top-ranking VPs

	VP ID	X (m)	Y (m)	Z (m)	Yaw (°)	Tilt (°)	Coverage (%)
WP1	VP1	44	1	22	38	58	100
	VP2	29	7	14	29	58	100
	VP3	41	1	22	29	58	100
	VP4	40	5	16	29	58	100
	VP5	44	6	15	31	58	100
WP2	VP6	19	58	35	55	283	96.19
	VP7	19	59	30	56	290	95.67
	VP8	19	67	35	53	280	95.44
	VP9	19	60	27	55	280	94.44
	VP10	19	72	35	58	274	93.92
WP3	VP11	18	32	33	56	279	92.79
	VP12	18	38	35	56	279	91.67
	VP13	18	35	35	56	279	91.61
	VP14	18	32	28	56	279	91.37
	VP15	18	42	35	56	279	91.21
WP4	VP16	39	-2	30	41	143	100
	VP17	76	-2	14	23	222	100
	VP18	76	-2	24	41	222	100
	VP19	38	-8	26	41	143	100
	VP20	36	-8	25	41	143	100

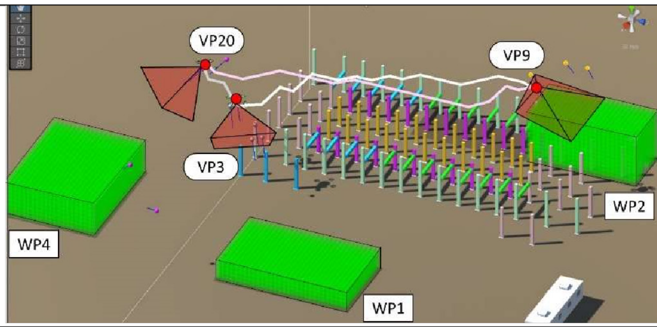
With the top-ranking VPs, the path planning module generates the optimized path in each duration, as shown in Figure 5. Then, the total hovering duration is calculated from the travel cost and the cycle path duration that has been explained in Section 3.2. During ΔT_1, the optimal path is VP3-VP9-VP3, as shown in Figure 5(a). The total travel cost between these VPs was 10.3 seconds, while the total amount of time spent hovering at these locations was 109.7 seconds. During ΔT_2, the optimal path is VP3-VP20-VP9-VP3 (Figure 5(b)). The total travel cost is 11.3 s. The total amount of time spent hovering at these VPs is 108.7 seconds. During ΔT_3, the optimal path is VP3-VP14-VP19-VP3 (Figure 5(c)). The total travel cost is 8.3s. The total amount of time spent hovering at these VPs is 111.7 seconds. The breakdown of the hovering durations for each of the selected VPs and the travel costs are then calculated, as shown in the figure. As a result of the differing ascent and descent speeds, the travel cost between two points at different heights can vary. This explains why the travel cost from VP9 to VP3 and the travel cost from VP9 to VP3 are different.

Finally, in the validation, the CP coverage is calculated. The CP coverages of the entire cycle path in ΔT_1, ΔT_2, and ΔT_3 are 0.881, 0.883, and 0.907, respectively. The results indicate that the method can efficiently identify the optimal path, which enables the collection of high-quality hovering videos of the specific 4D workspaces.



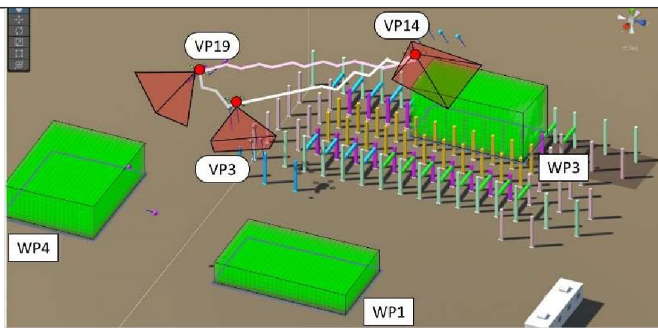
Action	Duration (s)
Hovering at VP3	45.5
Traveling VP3 - VP9	5.0
Hovering at VP9	64.2
Traveling VP9 – VP3	5.3
Total	120.0

(a) ΔT_1



Action	Duration (s)
Hovering at VP3	31.9
Traveling VP3 – VP20	1.0
Hovering at VP20	31.9
Traveling VP20 – VP9	5.0
Hovering at VP9	44.9
Traveling VP9 – VP3	5.3
Total	120.0

(b) ΔT_2



Action	Duration (s)
Hovering at VP3	32.8
Traveling VP3 – VP14	3.4
Hovering at VP14	46.2
Traveling VP14 – VP19	3.3
Hovering at VP19	32.8
Traveling VP19 – VP3	1.5
Total	120.0

(c) ΔT_3

Figure 5 Path optimization

4. Conclusions and Future Work

In this paper, a method is proposed for optimizing the path of a CE-UAV to collect videos of dynamic objects on construction sites. The proposed method involves a simulation-based VP optimization that identifies the top-ranking VPs for various workspaces. Subsequently, a GA algorithm is applied to minimize the travel cost by solving the GTSP based on the identified VPs, which generates an optimal path for data collection by the CE-UAV. To evaluate the proposed method, a case study is conducted using a prototype system developed with Unity and Python. The results demonstrate that the method can effectively identify VPs with excellent workspace coverage and generate an optimal path with the least travel cost.

Future work will focus on three aspects that improve the proposed method's effectiveness, efficiency, and applicability in real-world scenarios. First, a sensitivity analysis will be conducted to optimize the parameters of the first GA for identifying top-ranking VPs. The analysis aims to prevent premature convergence, ensure diversity in solutions, and identify all optimal solutions in the search spaces. Second, further development will be carried out to enhance the efficiency of the prototype system. Third, in order to validate the general feasibility of the proposed method, additional tests will be conducted using various construction projects to evaluate the reliability and robustness of the proposed method.

References

[1] S. Alizadehsalehi and I. Yitmen, “The Impact of Field Data Capturing Technologies on Automated Construction Project Progress Monitoring,” Procedia Eng., vol. 161, Jan. 2016, doi: 10.1016/j.proeng.2016.08.504.

[2] J. Kim, Y. Ham, Y. Chung, and S. Chi, “Systematic Camera Placement Framework for Operation-Level Visual Monitoring on Construction Jobsites,” J. Constr. Eng. Manag., vol. 145, no. 4, Apr. 2019, doi: 10.1061/(ASCE)CO.1943-7862.0001636.

[3] X. Chen, Y. Zhu, H. Chen, Y. Ouyang, X. Luo, and X. Wu, “BIM-based optimization of camera placement for indoor construction monitoring considering the construction schedule,” Autom. Constr., vol. 130, Oct. 2021, doi: 10.1016/j.autcon.2021.103825.

[4] S. V.-T. Tran, T. L. Nguyen, H.-L. Chi, D. Lee, and C. Park, “Generative planning for construction safety surveillance camera installation in 4D BIM environment,” Autom. Constr., vol. 134, Feb. 2022, doi: 10.1016/j.autcon.2021.104103.

[5] A. Albahri and A. Hammad, “Simulation-based optimization of PTZ camera placement and movement plan in buildings using BIM,” Autom. Constr. (Under review)

[6] K. Asadi, A. Kalkunte Suresh, A. Ender, S. Gotad, S. Maniyar, S. Anand, et al., “An integrated UGV-UAV system for construction site data collection,” Autom. Constr., vol. 112, Apr. 2020, doi: 10.1016/j.autcon.2019.103068.

[7] Y. Ham, K. K. Han, J. J. Lin, and M. Golparvar-Fard, “Visual monitoring of civil infrastructure systems via camera-equipped Unmanned Aerial Vehicles (UAVs): a review of related works,” Vis. Eng., vol. 4, no. 1, Jan. 2016, doi: 10.1186/s40327-015-0029z.

[8] I. Jeelani and M. Gheisari, “Safety challenges of UAV integration in construction: Conceptual analysis and future research roadmap,” Saf. Sci., vol. 144, Dec. 2021, doi: 10.1016/j.ssci.2021.105473.

[9] A. Ibrahim, M. Golparvar-Fard, and K. El-Rayes, “Multiobjective Optimization of Reality Capture Plans for Computer Vision–Driven Construction Monitoring with Camera-Equipped UAVs,” J. Comput. Civ. Eng., vol. 36, no. 5, Sep. 2022, doi: 10.1061/(ASCE)CP.1943-5487.0001032.

[10] X. Zheng, F. Wang, and Z. Li, “A multi-UAV cooperative route planning methodology for 3D fine-resolution building model reconstruction,” ISPRS J. Photogramm. Remote Sens., vol. 146, Dec. 2018, doi: 10.1016/j.isprsjprs.2018.11.004.

[11] S. Ivić, B. Crnković, L. Grbčić, and L. Matleković, “Multi-UAV trajectory planning for 3D visual inspection of complex structures,” Autom. Constr., vol. 147, Mar. 2023, doi: 10.1016/j.autcon.2022.104709.

[12] A. H. Albahri and A. Hammad, “A novel method for calculating camera coverage in buildings using BIM,” J. Inf. Technol. Constr. ITcon, vol. 22, no. 2, Jan. 2017.

[13] L. V. Snyder and M. S. Daskin, “A random-key genetic algorithm for the generalized traveling salesman problem,” Eur. J. Oper. Res., vol. 174, no. 1, Oct. 2006, doi: 10.1016/j.ejor.2004.09.057.

[14] U. Technologies, “Unity - Manual: Unity User Manual 2021.3 (LTS).” https://docs.unity3d.com/Manual/index.html (accessed Apr. 10, 2023).

[15] “Python Documentation contents — Python 3.11.3 documentation.” https://docs.python.org/3/contents.html (accessed Apr. 10, 2023).

[16] “PyGAD - Python Genetic Algorithm! — PyGAD 3.0.0 documentation.” https://pygad.readthedocs.io/en/latest/ (accessed Apr. 10, 2023).

[17] N. Bolourian and A. Hammad, “LiDAR-equipped UAV path planning considering potential locations of defects for bridge inspection,” Autom. Constr., vol. 117, Sep. 2020, doi: 10.1016/j.autcon.2020.103250.

UNMANNED AERIAL SYSTEMS FOR SAFETY MONITORING IN CONSTRUCTION: EFFECT ON SAFETY PERFORMANCE

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Abstract

Despite recent improvements in construction safety, the construction industry remains one of the major contributors to the number of work-related injuries and fatalities. Unsafe site conditions and unsafe behavior by workers are the main reasons behind construction accidents and accordingly these factors should be continuously monitored. The application of unmanned aerial systems (UAS) for safety monitoring is currently gaining attention in the construction industry. However, the long-term effect of the use of such a system on the safety performance of a construction site is still unknown and scarcely discussed in the literature. The objective of this study is to devise an agent-based modeling tool to examine the change in the safety performance of a construction site when using a UAS for safety inspection. Safety performance is measured using three types of indicators: incident rate, safety behavior and hazards reported. Moreover, the safety performance is explored when varying an important feature of the project, which is the level of site risk. The results show a total decrease of 13.61% in the unsafe behavior of workers. Moreover, the calculated mean incident rate at the end of this year is 0.63 which is lower than the incident rate of nonfatal occupational injuries in the construction industry in 2021 which was 2.7. Finally, it is found that 79% of hazards are detected using the UAS. However, the conducted tests show better results in projects with high levels of risk. The study contribution lies in providing safety managers and practitioners with a preliminary idea about the practical benefits of drones when used for safety monitoring, as well as the chance to understand, based on the nature of the project, whether employing the UAS can add value to their system.

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Keywords: agent-based modelling, construction safety, safety performance, unmanned aerial system (UAS).

1. Introduction

Although a significant improvement has been recently witnessed in the area of construction safety, the construction industry remains one of the major contributors, among other industries, to the number of work-related injuries and fatalities [1]. The reasons behind accidents on construction sites are mainly attributed to unsafe conditions and unsafe acts [2]. A standardized observation system for these conditions on site is necessary to monitor and improve the safety performance [3]. Unfortunately, the common practice of safety inspection by walking around the site is a very time consuming and tedious process [27], especially in large and complex building projects as well as heavy civil construction projects.

Advances in construction technology, however, have presented the industry with great potential for better control over and governance of the construction process. Specifically, the use of drones has recently been introduced into the world of construction. Drones are Unmanned Aerial Vehicles that can be managed without a pilot on board and are navigated and controlled either remotely through human intervention or autonomously. Moreover, the term UAS is sometimes used to describe the system that includes in addition to one or several unmanned aerial vehicles, the ground control station or device as well as any other needed elements like installed cameras or sensors [4]. The use of a UAS on an actual construction site for the purpose of safety inspection has been scarcely documented in the literature and accordingly no data regarding the efficiency of the use of such a system for improving the safety performance of a construction site has been presented. Since the collection of this type of data needs a long time with application in several projects, this study instead employs agent-based modelling to simulate the dynamics of a real construction site. The aim of this study is to understand the long-term effects of using drones for safety inspections. The results will aid project managers in choosing the appropriate safety system that can provide a continuous evaluation measure for the safety conditions and acts on site for the aim of minimizing the number of accidents and near misses.

2. Literature Review

2.1. Safety in construction

Abdelhamid & Everett [5] indicated that all accidents occur due to unsafe conditions or unsafe acts. Environment-based safety management focuses on the elimination of unsafe conditions, while human-based safety management is directed towards reducing unsafe acts. The latter, however, is more difficult to achieve since unsafe acts by humans or workers specifically are related to their mental process and their safety attitudes which are difficult to observe, quantify, and change [6]. According to Teo et al. [7], workers exhibit unsafe behavior either due to lack of knowledge or due to poor safety attitudes. In order to change workers' unsafe behavior, the mechanism of safety behavior should be well understood, especially since the process that leads to this behavior is not solely related to internal aspects of the worker but also to other external factors.

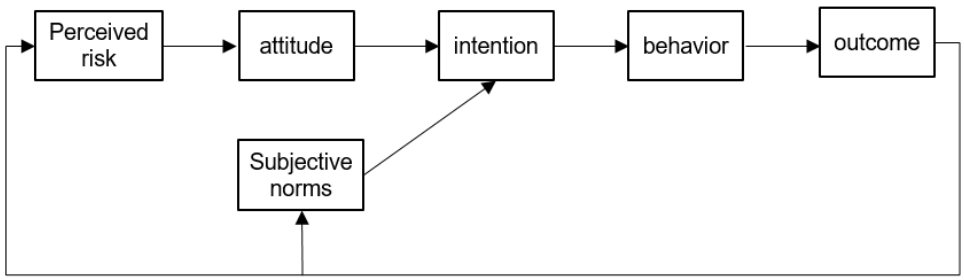

Fig. 1. Workers' mental process in relation to their safety behavior [6,8,10]

As shown in Figure 1, the theory of planned behavior traces back behavior to behavioral intentions which are affected by factors such as the attitude of the worker and the subjective norms [8]. The safety attitude of a worker is developed through the perceived risks that this worker acquires from diverse sources [6]. Risk perception is defined as "the subjective judgment that people make about the characteristics and severity of a risk" [9]. Subjective norms represent "a person's perceptions of significant others' expectations of his behaviour" [10]. For the case of construction workers, significant others are co-workers and management [10]. The final behavior implemented by the worker leads to a certain outcome that could again affect the attitude and subjective norms thus forming a feedback loop [6].

2.2. Safety performance and indicators

Lagging indicators such as the Total Recordable Incident Rate show the magnitude of the occurrence of accidents and are reactive in the sense that they collect after the fact statistics. Although these indicators are easy to collect and easily understood [11], they don't provide any insight about the specific items that should be addressed in the system to improve this performance [12]. The need for more proactive safety measures lead to the introduction of leading indicators for the measurement of safety performance. These indicators provide metrics for monitoring the process during its implementation and thus giving the chance for managers to proactively respond to the collected results [12]. Ideally, a combination of both lagging and leading indicators should be used to measure the safety performance. In the current study, safety behavior and hazards reported will be used as leading indicators, while incident rate will be used as lagging indicator.

2.3. Use of drones for enhancing safety in construction

Unmanned aerial vehicles (UAV) can improve safety management systems by being an effective tool for monitoring the conditions on site and hence aiding in conducting safety inspections which are known for being difficult and time consuming, but crucial for maintaining the safety level on site [4,13]. The drone can collect visual assets quickly and as frequently as necessary with the capability of transmitting the gathered data to the ground control station in real-time and thus allowing for instantaneous intervention where needed [4,14]. Managers can get the chance to constantly visualize dangerous activities without physically being present at the location. Irizarry & Costa [14] tested the possible applications of unmanned aerial systems for construction management issues and found that most of the collected visual assets (pictures and videos) helped in the identification of safety-related issues.

Irizarry et al. [4] indicated that for safety inspections to be effective, they should be characterized by being frequent, having direct observations of conditions and methods, and providing direct interaction between the inspector and the workers. In addition to satisfying the first characteristic, some drones can allow for direct observation through, first, easy navigation control by a simple user interface on the inspector's personal smartphone or tablet, and second, the ability to issue real-time videos to this interface [4]. Moreover, drones can be equipped with communication devices for direct interaction [14].

Experiments performed with drones on the field showed that some of the safety-related issues that can be observed from the collected assets are: "damaged safety nets, missing safety guardrails, improper material storage and debris, stairs without fall protection, workers on the edge of a roof without appropriate fall protection, workers without hard-hats and personal fall arrest systems, safety platforms not installed on the entire perimeter of the building and safety platforms with uncompleted floorboard, inappropriate use of hard-hats, and safety platforms with unforeseen overload (people and scaffolding)" [14,13]. Kim & Irizarry [15] indicated that the performance of UAVs can be influenced by the features of the used UAS, the project characteristics, as well as the project team features. Such features include: "Easy user interface for UAS operation, battery life of the UAS, maximum visible angle of the UAS camera, project size, duration, and complexity, team's prior experience with UAS, adequacy of training or education for UAS use as safety monitoring system, etc."

2.4. Agent-based modelling

The construction industry is known for being very dynamic and evolving such that frequent changes have become a rule instead of an exception. Moreover, construction projects include numerous participants from various organizations socially interacting with each other and the site components, making these projects perfect candidates for presentation through agent-based modelling. Agent-based simulation is a method that uses a bottom-up approach to capture emergent phenomena of a set of agents that interact with each other and the surrounding environment [16]. In the area of construction safety, the first attempt to use agent-based modelling was done by Walsh & Sawhney [16].

3. Conceptual Framework

The conceptual model is focused around two main concepts. The first is the cognitive process of construction workers' safety behaviour adopted from Choi et al. [17], and the second is the process of safety inspection using a UAS as described and tested by de Melo et al. [13].

The construction site is characterized by the level of risk. Site risk is represented in the model by the probability that a worker gets exposed to an unsafe condition as well as the severity of the risk that workers will be exposed to under the unsafe condition [18]. Walsh & Sawhney [16] argued that going into excessive details of the actual geometry of the construction site and its changes with time might in fact cause ambiguities in the basic behaviour of the model instead of reinforcing it. Therefore, a simple square layout is chosen to represent the construction project, having a length of 50m and a width of 50m, thus an area of 2500m2. Figure 2 summarizes the conceptual framework when a UAS is employed for safety inspection.

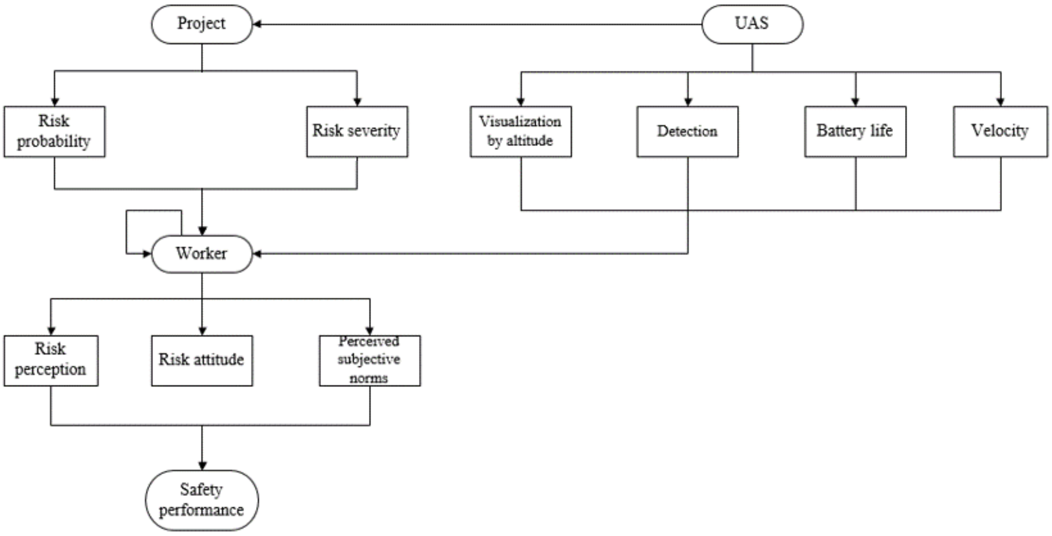

Figure 2 – Conceptual Framework

3.1. Cognitive process of workers' safety behavior

Construction workers move around the site searching for work. During the execution of a task, workers can be subject to unsafe conditions and whether they commit an unsafe behavior will be determined through the portrayed cognitive process in the model. All the equations in this section are adopted from Choi & Lee [19]. The actual risk on site is perceived differently between one worker and another based on the perceiving coefficient [6]. However, even if two workers perceive a risk similarly, their reaction to the perceived risk is different. This reaction is a consequence of the acceptable risk by each worker. Therefore, the choice of safe or unsafe behaviour will be based on the below Equations 1 & 2 in the model:

if $RA < PR$, the worker will behave safely, (1)

but if $RA > PR$, the worker will behave unsafely, (2)

where RA = risk acceptance of the worker and PR = perceived risk by the worker.

The perceived risk is determined based on the actual risk in the location and the risk perceiving coefficient of the worker, such that:

$$PR = RP_{coef} \times AR \tag{3}$$

where RPcoeff = risk perceiving coefficient of the worker and AR = actual risk in the area.

The risk perceiving coefficient is affected by the worker's previous experience, knowledge about risk and safety, as well as his risk attitude [20]. Risk attitude shows the affinity of the worker towards taking risk. The attitude of the worker will change if this worker undergoes a near miss or an accident. In such a case, the worker will become more risk averse. Conversely, the attitude of the worker will become more risk-seeking in the cases when the worker behaves unsafely but is neither warned by management nor does he experience a near miss or an accident. This is because in this case the worker will underestimate the likelihood of an accident [10]. The risk perceiving coefficient will change based on the change of the attitude.

As for the risk acceptance, it is determined by both internal factors of the worker such as attitude, as well as the interaction with external factors such as other coworkers, representing the workgroup norm, and the drone, representing the management norm [17]. Hence, the risk acceptance is calculated based on Equation 5:

$$RA = (1 - SI) \times Att + SI \times (PJI \times MN + (1 - PJI) \times WN) \quad (5)$$

where SI = weight on social influence, PJI = project identification, MN = management norm as perceived by the worker, and WN = workgroup norm as perceived by the worker.

The weight on social influence represents the extent to which the worker is affected by social factors. This factor intensifies the effect of management and workgroup norms and attenuates the influence of the personal factor which is the attitude. Moreover, project identification represents the extent to which workers identify themselves with the project [17]. Workers with stronger identification with the project will probably be less influenced by the workgroup norm and more willing to comply to management norms. Thus, this factor strengthens the effect of management norms while it weakens the effect of workgroup norms [17]. Both findings are reflected in Equation 5.

The workgroup norm is the worker's perception of the acceptable risk of his coworkers taking into consideration the amount of info that he can retain based on his memory. In the model, the worker can only observe co-workers close to him. While working, the worker observes his co-workers and updates his perceived workgroup norm by taking into consideration the average of the coworkers' risk acceptance as perceived by him according to Equation 6:

$$WN_i = (1 - \frac{1}{m}) \times WN_i^{prev.} + \frac{1}{m} \times (\frac{1}{k} \times \sum_{0}^{k} PRA^n) \quad (6)$$

where m = memory duration, k = total number of co-workers close to the worker i, and PRA^n is the risk acceptance of co-worker n as perceived by the worker i.

The management norm is the worker's perception of the acceptable risk by management in the project. The worker updates his perceived management norm according to Equation 7.

$$MN_i = (1 - \frac{1}{m}) \times MN_i^{prev.} + \frac{1}{m} \times PMA \quad (7)$$

where PMA is the management risk acceptance as perceived by the worker.

3.2. Safety inspection using an unmanned aerial system

A UAS consisting of one drone mounted with a camera and a ground control station (a tablet for example) will be used for the monitoring process and the communication between management and the workers will be done through the UAV. The assumption is that the drone will navigate the site externally without entering inside the built part of the buildings. During one complete inspection mission, the drone will inspect the site at three different levels: overview, medium view, and close-up view.

In order to have an efficient inspection mission, de Melo et al. [13] advised that the flight mission be well planned by defining the trajectory to be followed by the drone including the take-off location and the landing operation while taking into consideration all safety requirements. The path of the drone is created such that all the site area is covered by the drone flight at each level. The drone will move a certain distance then stop for a certain duration to capture photos and videos and then moves again repeating this process until the whole site area is covered. However, since in reality the drone will have to maneuver in order to avoid obstacles and since this issue is not taken into consideration in the used paths, the assigned speed for the drone in the model is decreased by 20% in order to account for this additional time.

Based on the study by de Melo et al. [13], only certain percentage of requirements will be visualized at each level. Figure 3 shows the percentage of safety inspection requirements visualized at each level for two projects: A (horizontal-type) and B (vertical-type). Note that for the overview inspection, only unsafe conditions will be visualized since the behaviour of workers is very difficult to detect at such an elevated altitude.

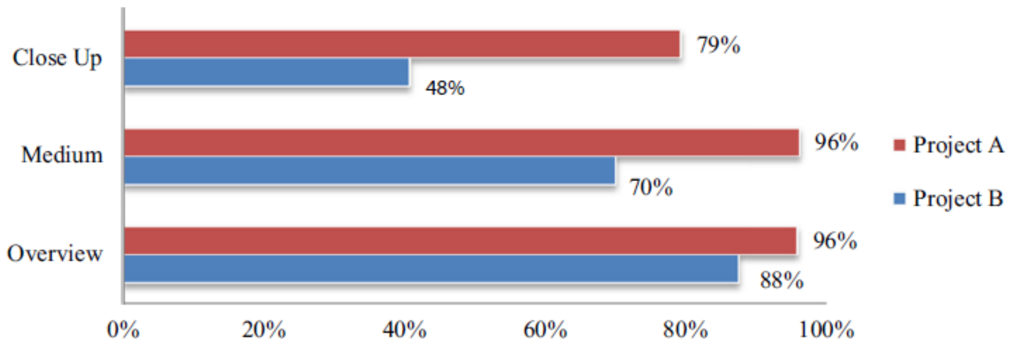

Figure 3 – Percentage of safety inspection requirements visualized by snapshots [13]

The photos and videos that are taken by the camera are scanned for detection through a certain algorithm and again only certain percentage of requirements will be detected based on the precision of the algorithm. The mechanism for detection along with its performance are adopted from the study by Mneymneh et al. [21]. This algorithm can detect 86% of instances in outdoor near range visual assets and 84% in outdoor far range visual assets. The time needed for the detection of the unsafe acts/conditions by the algorithm is approximated for each area based on the findings of this study.

The calculation of the footprint of the camera depends on the characteristics of the used camera as well as the height at which the camera is operating from the ground. The drone is assumed to follow a flat flying motion and the dimensions of the footprint, as shown in Figure 4 are calculated using the methods and equations from the study by Chen et al. [22].

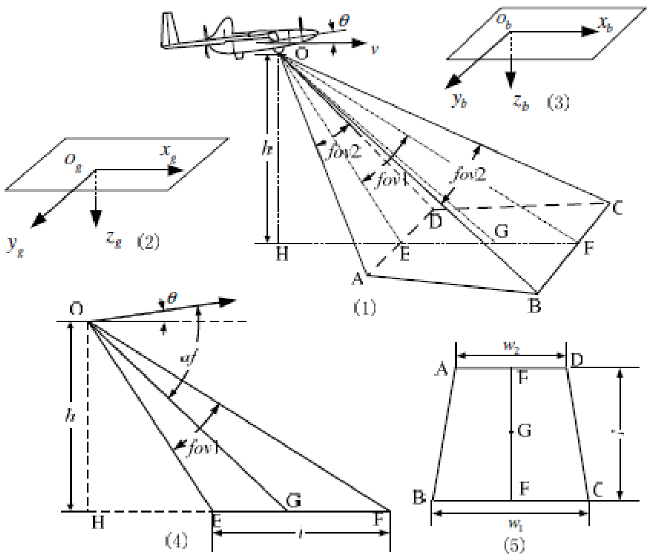

Figure 4 – The camera footprint in flat flying motion [22]

Since the battery of the drone has a certain lifespan, the drone will need to return for charging or replacement of the battery when the battery is near empty. Manufacturers usually advise that the drone returns when the battery charging level reaches 30% [23]. This inspection by the drone can easily be repeated as much as needed per day since no physical effort will be required and since the safety of any personnel is not compromised. A timeout is set between inspections to take into consideration the possible need for battery replacement.

Based on the above-described process, when an unsafe condition is encountered, the concerned party will be informed by management to resolve the problem. Moreover, when the UAS detects an unsafe behaviour by a worker, the worker will be warned through direct communication.

4. Results

The conceptual model is translated into a simulation model and the safety indicators calculated.

4.1. Incident Rate

The first indicator used is a lagging indicator which is the incident rate. Equation 8 is used to calculate the incident rate and it is adopted from OSHA (Occupational Safety and Health Administration):

$$\text{Total Recordable Incident Rate} = \frac{\text{Number of recordable cases} * 200{,}000}{\text{Number of total labor hours worked in the year}} \quad (8)$$

To get reliable results, the model was run 100 times. Figure 5 shows the box plot for the incident rate for the 100 simulation runs. Note that the incident rate of nonfatal occupational injuries in the construction industry in 2021 was 2.7. We can see from the box plot that the calculated incident rate in the model is lower than 2.7 in all the conducted simulation runs.

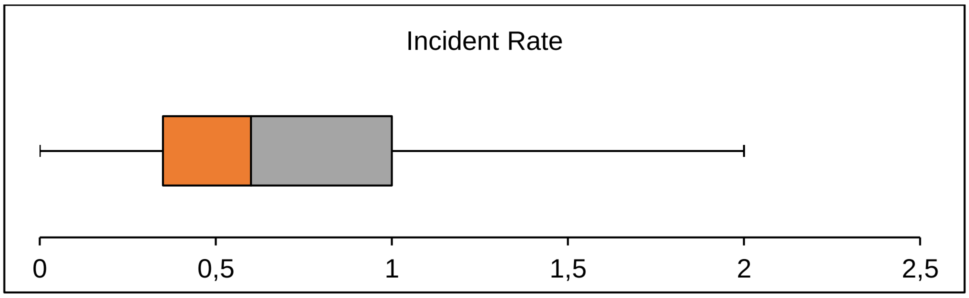

Figure 5 – Box plot for the incident rate of 100 simulation runs

4.2. Safety Behaviour

The second indicator is the safety behavior of workers which is a leading indicator. The safety behavior of workers is examined by tracking the change in the ratio of unsafe behavior with the progress of the project. The unsafe behavior ratio is calculated as shown in Equation 9 [24]:

$$\text{Unsafe Behavior} = \left(\frac{\text{Total observed unsafe behavior}}{\text{Total observed safe behaviour} + \text{Total observed unsafe behavior}}\right) * 100 \quad (9)$$

Figure 6 shows the change in the unsafe behavior ratio with time. The horizontal axis represents the time in hours in the simulation, bearing in mind that each 8 hours constitute one working day, and the vertical axis represents the ratio of unsafe behavior in percentage.

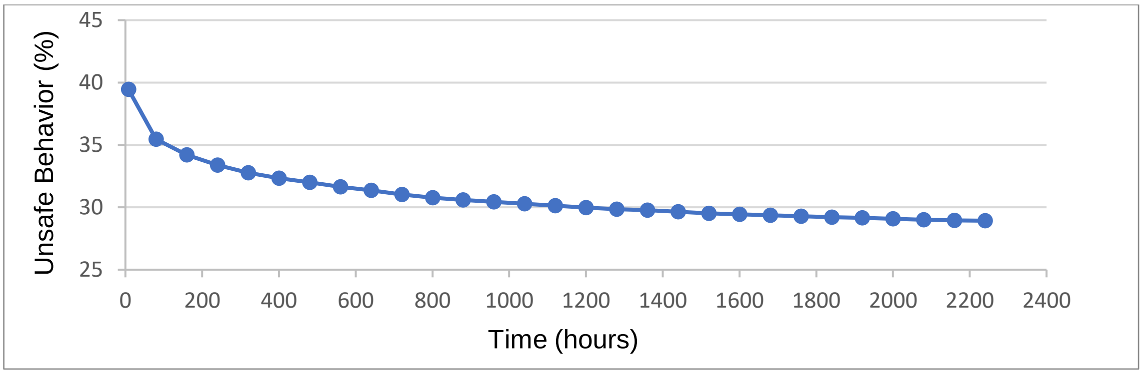

Figure 6 – Change of safety behavior of workers with time

The unsafe behaviour decreases at a fast rate in the beginning and then this rate decreases gradually until the curve levels out towards a minimum value at around 150 days. This is due to the fact that at the beginning three factors are all contributing together to the change in the risk acceptance of the worker: the personal risk attitude, the communication within the workgroup between workers, and the communication with management through the UAS. However, towards the end of the simulation, the effect of workers on each other is minimized since most of the workers will have reached a unified or similar value of perceived workgroup norm, bearing in mind that the study is done on the same work crews throughout all the simulation. For instance, five random workers were chosen and their individual unsafe behavior ratio plotted over time. As shown in Figure 7, the curves tend to converge until they reach similar values where they become steady. Moreover, since towards the end of the simulation, the unsafe behavior of the worker will have decreased, then they will not get a high chance of updating the risk acceptance through management intervention. Finally, it is impossible for the attitude of the workers to decrease infinitely with time and this is controlled in the model by setting upper and lower boundaries for the value of the attitude variable. This fact also effects the rate of decrease of the unsafe behaviour.

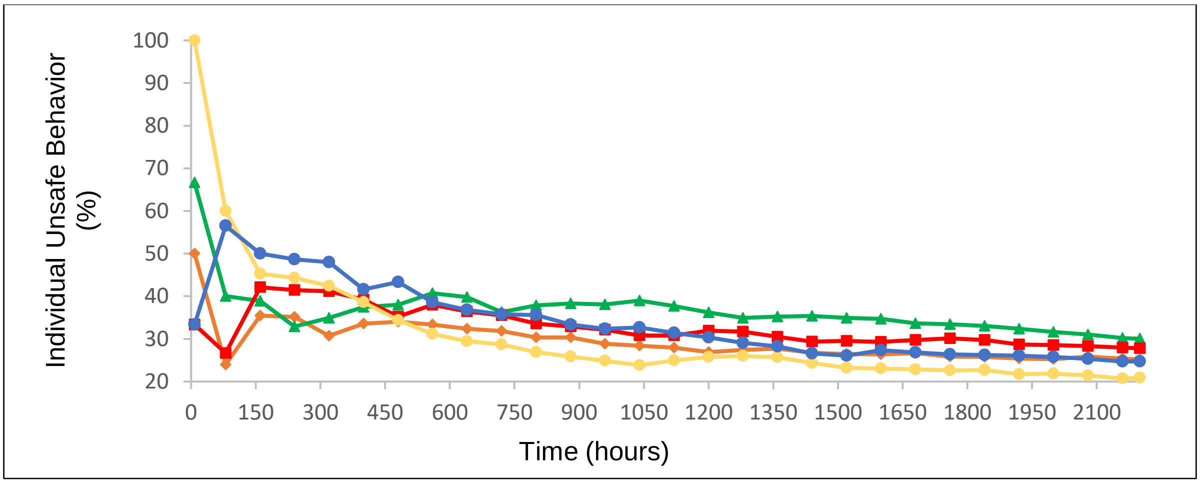

Figure 7 – Change of the individual safety behavior of workers

4.3. Hazards Reported

The third indicator used is also a leading indicator which is the number of hazards reported. This indicator shows the percentage of unsafe conditions that were detected throughout the project. It is calculated using Equation 10.

$$\text{Hazards Reported} = \left(\frac{\text{Total hazards detected}}{\text{Total number of hazards}}\right) * 100 \tag{10}$$

Figure 8 shows the box plot for the % of hazards detected in 100 simulation runs. The mean is 79.07%.

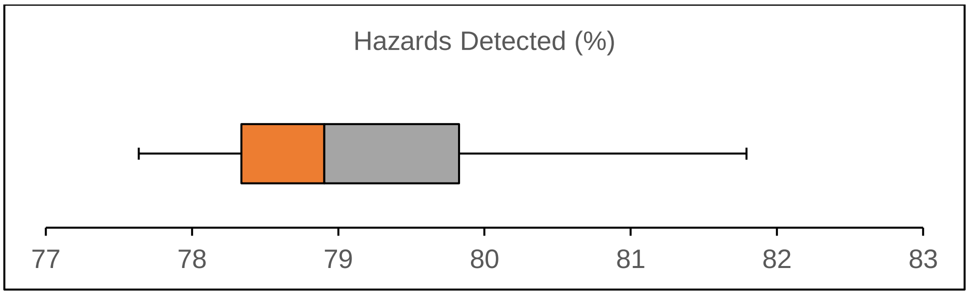

Figure 8 – Box plot for the % of hazards detected of 100 simulation runs

The fact that the percentage of unsafe conditions detected by the UAS is high despite the restrictions imposed (visualization & detection by algorithm) is highly related to the frequency of inspections. The model showed that for the given site area, 8 missions in one day were able to be conducted. So, if an item was not visualized or detected in the first mission, for example, there is a good probability that it will be visualized or detected in another mission before the condition changes. This is to some extent a true reflection of reality because if the UAS fails to clearly inspect a certain area, it can be sent again for inspection when and as much as needed before the conditions in this area change.

5. Simulation experiments and results

To understand the effect of the characteristics of the project on the performance of the UAS, an experiment was formulated.

5.1. Effect of Site Risk

The effect of the level of risk in the project was studied by modifying the site risk. The model was run under three scenarios: (1) low risk site conditions (2) moderate risk site conditions (baseline), and (3) high risk site conditions. This attribute is used as a main characteristic of the project since in reality different construction trades and activities impose different levels of risk on workers [18]. As such, even within the same project the risk can differ in different periods or phases of the project [25]. As shown in Figure 9, the use of the UAS is mostly effective for the case of high-risk site conditions. It is important to note that the final values of unsafe behavior reached in both the moderate and the high site risk are smaller than the final value reached in the low site risk. This is because in low-risk sites, workers will not get a big chance of improving their attitude since the number of situations where they will be susceptible to risk is already very low.

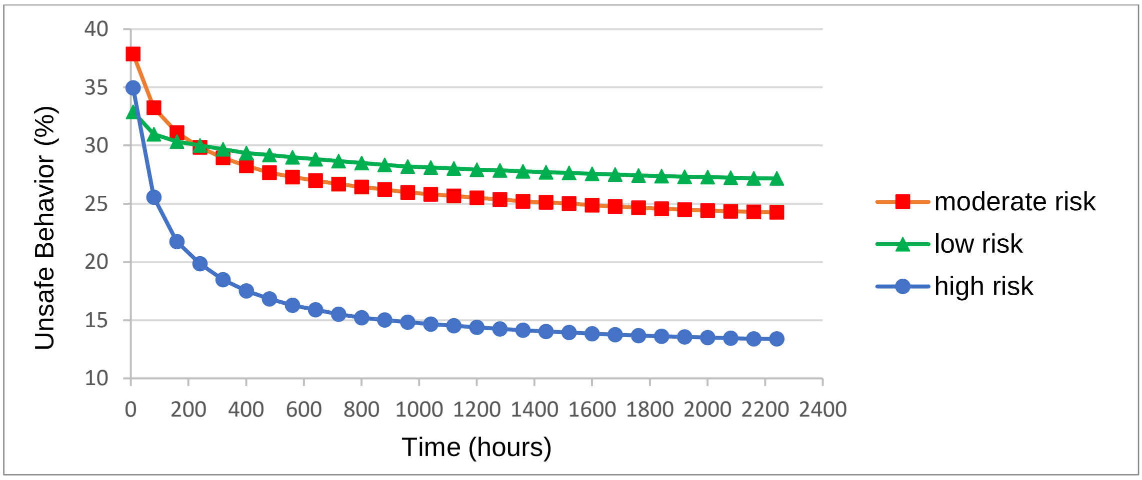

Figure 9 – Effect of the site risk on the safety behavior of workers when employing a UAS

6. Conclusion

An agent-based modelling tool was established to study the development of the safety performance of a construction site when using an unmanned aerial system for safety inspection. The results showed that this system can effectively improve the safety performance of the project. Moreover, the conducted experiments showed that the use of the UAS yields best results in high-risk projects. However, including UAVs in the safety management system must be accompanied with a set of standardized procedures for adequately planning the flight mission, collecting and storing the data, analysing this data, and taking the appropriate immediate and future managerial actions accordingly. Regarding the limitations of the study, the model only considers the inspection of the project externally. The behaviour of a UAV in indoor spaces differs completely. This issue can be considered in future studies. This study can be extended further by collecting real information from construction sites regarding all assumed variables in the model to further validate it. Furthermore, it would be interesting to back up the study with cost analysis and comparison between the use of a safety inspector versus a UAS for safety monitoring.

References

[1] R. Awwad, O. El Souki, and M. Jabbour, “Construction safety practices and challenges in a Middle Eastern developing country,” Safety Science, vol. 83, pp. 1–11, Mar. 2016, doi: 10.1016/j.ssci.2015.10.016.

[2] J. Jehring and H. W. Heinrich, “Industrial Accident Prevention: A Scientific Approach,” Industrial and Labor Relations Review, vol. 4, no. 4, p. 609, Jul. 1951, doi: 10.2307/2518508.

[3] H. Laitinen, M. Marjamäki, and K. Päivärinta, “The validity of the TR safety observation method on building construction,” Accident Analysis & Prevention, vol. 31, no. 5, pp. 463–472, Sep. 1999, doi: 10.1016/s0001-4575(98)00084-0.

[4] Irizarry, J., Gheisari, M., & Walker, B. N. (2012), “Usability assessment of drone technology as safety inspection tools,” Journal of Information Technology in Construction, vol. 17, pp. 194-212, 2012.

[5] T. S. Abdelhamid and J. G. Everett, “Identifying Root Causes of Construction Accidents,” Journal of Construction Engineering and Management, vol. 126, no. 1, pp. 52–60, Jan. 2000, doi: 10.1061/(asce)0733-9364(2000)126:1(52).

[6] M. Shin, H.-S. Lee, M. Park, M. Moon, and S. Han, “A system dynamics approach for modeling construction workers’ safety attitudes and behaviors,” Accident Analysis & Prevention, vol. 68, pp. 95–105, Jul. 2014, doi: 10.1016/j.aap.2013.09.019.

[7] E. Ai Lin Teo, F. Yean Yng Ling, and D. Sern Yau Ong, “Fostering safe work behaviour in workers at construction sites,” Engineering, Construction and Architectural Management, vol. 12, no. 4, pp. 410–422, Aug. 2005, doi: 10.1108/09699980510608848.

[8] I. Ajzen, “The theory of planned behavior, ”Organizational Behavior and Human Decision Processes, vol. 50, no. 2, pp. 179–211, Dec. 1991, doi: 10.1016/0749-5978(91)90020-t.

[9] Lavino, Joana G. & Neumann, Rasmus B. (eds.), “Psychology of Risk Perception”, Nova Science Publishers. Isbn: 1608769607

[10] M. Zhang and D. Fang, “A cognitive analysis of why Chinese scaffolders do not use safety harnesses in construction,” Construction Management and Economics, vol. 31, no. 3, pp. 207–222, Mar. 2013, doi: 10.1080/01446193.2013.764000.

[11] H. Lingard, “Occupational health and safety in the construction industry,” Construction Management and Economics, vol. 31, no. 6, pp. 505–514, Jun. 2013, doi: 10.1080/01446193.2013.816435.

[12] J. Hinze, S. Thurman, and A. Wehle, “Leading indicators of construction safety performance,” Safety Science, vol. 51, no. 1, pp. 23–28, Jan. 2013, doi: 10.1016/j.ssci.2012.05.016.

[13] R. R. S. de Melo, D. B. Costa, J. S. Álvares, and J. Irizarry, “Applicability of unmanned aerial system (UAS) for safety inspection on construction sites,” Safety Science, vol. 98, pp. 174–185, Oct. 2017, doi: 10.1016/j.ssci.2017.06.008.

[14] J. Irizarry and D. B. Costa, “Exploratory Study of Potential Applications of Unmanned Aerial Systems for Construction Management Tasks,” Journal of Management in Engineering, vol. 32, no. 3, May 2016, doi: 10.1061/(asce)me.1943-5479.0000422.

[15] S. Kim, J. Irizarry, and D. B. Costa, “Potential Factors Influencing the Performance of Unmanned Aerial System (UAS) Integrated Safety Control for Construction Worksites,” Construction Research Congress 2016, May 2016, doi: 10.1061/9780784479827.260.

[16] Walsh, Kenneth D., and Anil Sawhney, "Agent-based modeling of worker safety behavior at the construction vvorkface," 2004.

[17] B. Choi, S. Ahn, and S. Lee, “Role of Social Norms and Social Identifications in Safety Behavior of Construction Workers. I: Theoretical Model of Safety Behavior under Social Influence,” Journal of Construction Engineering and Management, vol. 143, no. 5, May 2017, doi: 10.1061/(asce)co.1943-7862.0001271.

[18] S. Choe and F. Leite, “Assessing Safety Risk among Different Construction Trades: Quantitative Approach,” Journal of Construction Engineering and Management, vol. 143, no. 5, May 2017, doi: 10.1061/(asce)co.1943-7862.0001237.

[19] B. Choi and S. Lee, “An Empirically Based Agent-Based Model of the Sociocognitive Process of Construction Workers’ Safety Behavior,” Journal of Construction Engineering and Management, vol. 144, no. 2, Feb. 2018, doi: 10.1061/(asce)co.1943-7862.0001421.

[20] K. Mearns and R. Flin, “Risk perception and attitudes to safety by personnel in the offshore oil and gas industry: a review,” Journal of Loss Prevention in the Process Industries, vol. 8, no. 5, pp. 299–305, Jan. 1995, doi: 10.1016/0950-4230(95)00032-v.

[21] B. E. Mneymneh, M. Abbas, and H. Khoury, “Vision-Based Framework for Intelligent Monitoring of Hardhat Wearing on Construction Sites,” Journal of Computing in Civil Engineering, vol. 33, no. 2, Mar. 2019, doi: 10.1061/(asce)cp.1943-5487.0000813.

[22] H. Chen, X.-M. Wang, Y.-S. Jiao, and Y. Li, “Research on search probability and camera footprint of region coverage for UAVs,” 2009 IEEE International Conference on Control and Automation, Dec. 2009, doi: 10.1109/icca.2009.5410419.

[23] Costa, D. B., De Melo, R. R., Álvares, J. S., & Bello, A. A, "Evaluating the performance of unmanned aerial vehicles for safety inspection," Boston, MA, USA pp. 23-32, 2016.

[24] Nasirzadeh, Farnad, Mostafa Khanzadi, and Mostafa Mir, "A hybrid simulation framework for modelling construction projects using agent-based modelling and system dynamics: an application to model construction workers' safety behavior," International Journal of Construction Management, vol. 18, pp. 132-143, 2018.

[25] B. Esmaeili and M. Hallowell, “Integration of safety risk data with highway construction schedules,” Construction Management and Economics, vol. 31, no. 6, pp. 528–541, Jun. 2013, doi: 10.1080/01446193.2012.739288.

A DECENTRALIZED MOBILE-BASED MORNING ASSEMBLY APPLICATION FOR CONSTRUCTION SITES WITH GPS-ASSISTANCE TECHNOLOGY AND INTUITIVE UI/UX

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Abstract

Morning Assembly in construction sites in Japan is an age-old practice that is influenced by tradition. One or more managers conduct this assembly by physically gathering construction workers in a designated place to relay information regarding tasks, safety, disasters, emergencies, Work Progress and many more. Typically, a bulletin board has been in use for this type of assembly. However, these assemblies are usually crowded, unmanaged and time-consuming. Besides this, workers are also less likely to pay full attention to the speaker due to the chaotic nature of the assembly. These assemblies can also be a ground for spreading infectious diseases like COVID-19 and others. Hence, with the aim of improving the overall assembly experience for both management and workers side, we propose an application that helps to conduct assemblies in a decentralized and secure manner. With this application, managers can conduct assembly and broadcast information directly to the worker's smartphone and hence eliminating the crowded and unmanaged nature of assemblies. This application uses the GPS location of the site and the registered worker's smartphone as an identification pair – which is then used to identify which worker is physically available inside which site. Once the worker is within the allowed range of the site, as determined by GPS data, information like site detail, disaster, and safety declaration of the current site along with images and videos is broadcasted to the worker. Site information is simply not broadcasted to devices located outside of the site range and designated time to avoid information leakage. Keeping workers' IT literacy in mind, the app is provided with a simple yet intuitive UI/UX to navigate through and gather assembly information. This novel application was tested in multiple construction sites on which it has helped to increase the productivity of managers and workers significantly.

Keywords: Construction, Construction Management, GPS, Mobile application, Morning Assembly

1. Introduction

Every day on construction sites, "Chourey" - a morning assembly in Japanese - is the first activity to take place before work begins. All workers gather at a designated location in the early morning to hear the site manager discuss tasks, safety precautions, emergency procedures, examples of potential hazards, and safety declarations. As depicted in Fig.1 [1], the traditional morning assembly typically involved all construction workers gathering in one location, where the site manager would give instructions using a bulletin board and displays.

The traditional method of conducting morning assembly had several shortcomings such as difficulty in hearing and understanding the information being shared, difficulty in viewing the bulletin board, forgetting the assembly contents during work, having to constantly check the bulletin board for information, potential privacy breaches, and issues with data collection and user access to safety declarations [2]. These problems not only hinder the productivity of construction management works but also decrease the productivity of the construction management works [3]. Furthermore, such physical gatherings being a hotspot for communicable diseases [4].

In our previous paper [1], we discussed about the development and implementation of an application for performing the assembly on the construction sites in a decentralized manner. The previous paper explains about the web application that uses QR code for accessing the site information [5]. The users (workers) need to open the app with the browser, login with their ID and Password every day and scan the designated QR code for getting access to the site's information [6]. The users are then able to get access every assembly information by the site manager on their mobile in the designated area and within the designated time. The flow of the user access process to the designated site information by using our previous application is shown in Fig. 2. This application was helpful in the construction sites, but the UI/UX part of this app was required to be enhanced for increasing the number of users [7].

The implementation process of our previous application [1] was simple but talking about the IT literacy of the construction workers, opening the application via browser, logging on in the application with the ID and password and then scanning the QR codes seems to be troublesome for the users. Which resulted in the decrease of the usage of the application. Understanding these problems from the construction sites, we think of solving these problems by enhancing the web application to mobile application by using the GPS assistance technology and intuitive UI/UX [8]. In this paper, we will be focusing about the terms mentioned above being implemented as mobile application [9].

Fig.1. Traditional way of morning assembly in Japanese Construction sites

Fig.2. Flow of the user access process to our previous application.

2. Objectives of the Novel application

In our previous approach, we mentioned about the web application for morning assembly in the construction sites. To make application more feasible for the users, we set the following objectives.

• To improve the overall assembly experience for both management and workers by using a decentralized, secure, and location-based method of conducting assemblies.

•To identify and securely broadcast relevant information to workers using GPS location and device identification pai [10].

•To simplify the process of gathering assembly information with a user-friendly interface, making it accessible to all workers regardless of their technical expertise, and increase the productivity of construction management works [11].

•To increase the number of users using our application for morning assembly in the sites.

3. Overview of the Novel application

To enhance the overall assembly experience for both management and workers, we propose the implementation of an innovative application that facilitates assemblies in a more decentralized and secure way. This application allows managers to conduct assemblies and broadcast information directly to the workers' smartphones, thereby eliminating the crowded and chaotic nature of traditional assemblies.

The application utilizes the GPS location of the construction site and the registered worker's smartphone as an identification pair, which is then used to identify which worker is physically present on which site [12].

Once the worker is within the allowed range of the site, as determined by GPS data, information such as site details, disaster, and safety declarations, as well as images and videos, are broadcasted to the worker's device. This ensures that site information is not broadcasted to devices located outside the site's range, thereby preventing any potential information leakage.

In addition, considering that many workers may not be proficient in IT, the application is designed with a simple yet intuitive user interface and user experience to ensure that workers can easily navigate through and gather assembly information. This simplifies the process and makes it more accessible for all workers, regardless of their level of technical expertise.

3.1. Technical overview of the Novel application

This novel application in an android-based native application [13]. The application is a device-based application. In this application, every mobile consists of their phone number and the phone numbers are allocated to the sites. During the initial settings of the mobile, the user input the phone number in the application and register the phone number as shown in Fig. 3. The system also consists of editing the registered number if it is entered wrong. The registered phone number must be allocated to the site in the initial phase for using the application.

The IT admin of the application will then allocate the registered phone number to the designated construction sites. The process of allocating the phone number is also called Device mapping in our technical terms. Once the mobile number is allocated with the sites, the user can get access to the sites depending on the designated browse range and time.

The manager of the site can create the information of the site from the manager account, where the system uses google map API for registering the address or the latitude and longitude of the site as shown in Fig. 4. The user application utilizes the GPS functionality of the device mapped with the sites to track the user's current location in real-time. The location of the device along with the authentication based on the workers smartphone helps to make the application secure. To access the sites, the GPS location of the device must be kept ON while using the application.

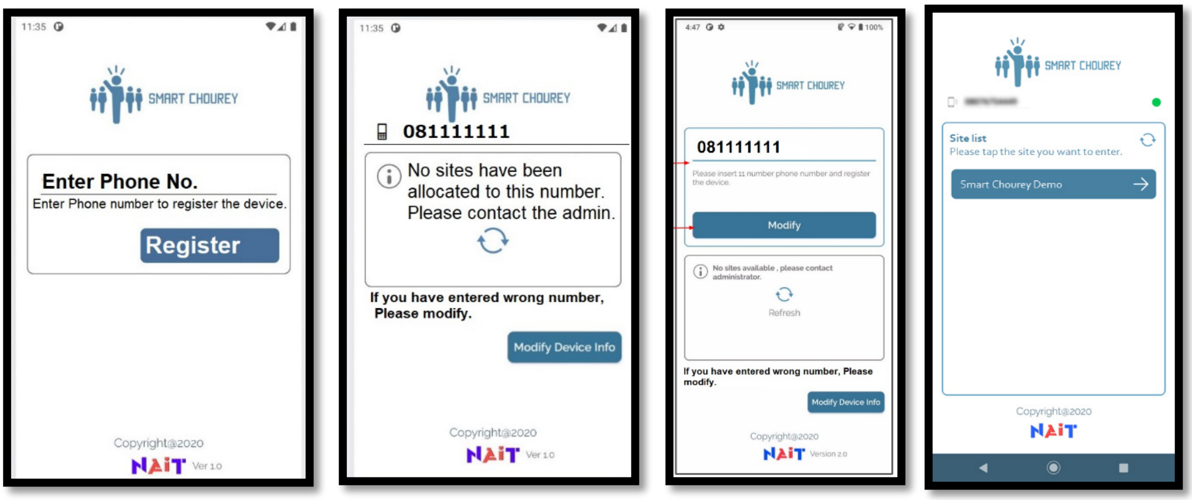


Fig.3. The flow showing the initial setting screen for registering and modifying the phone number and allocated sites.

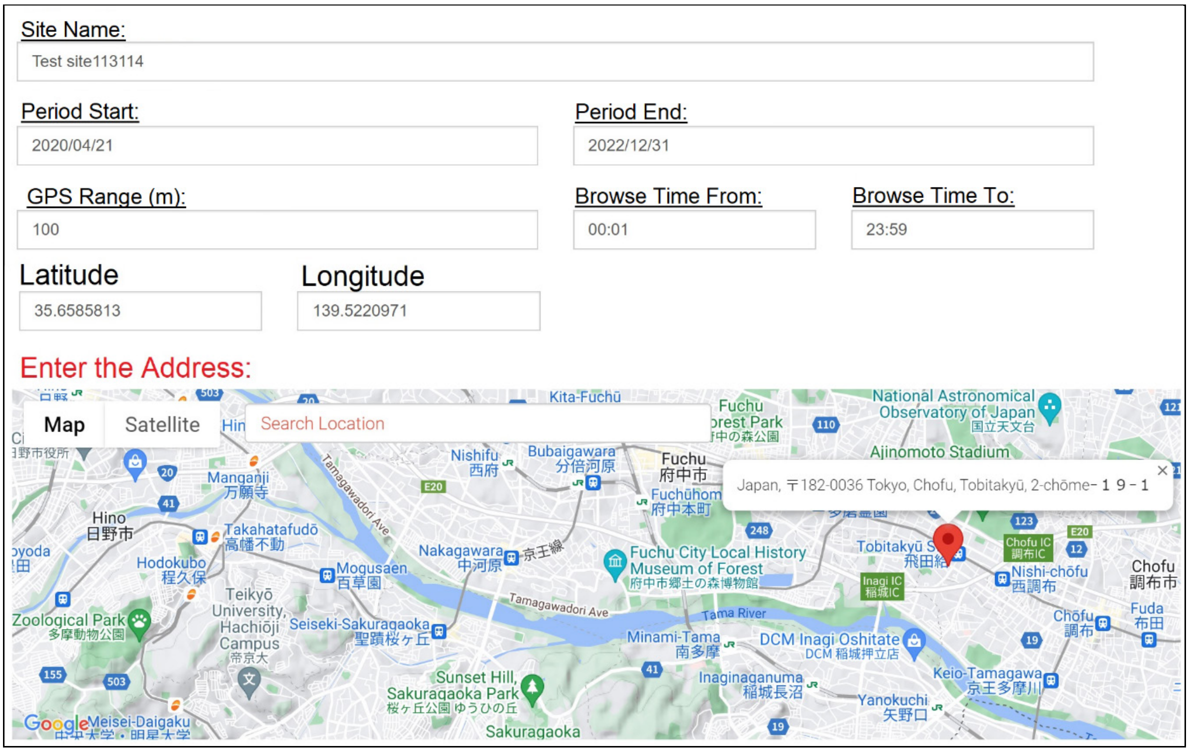
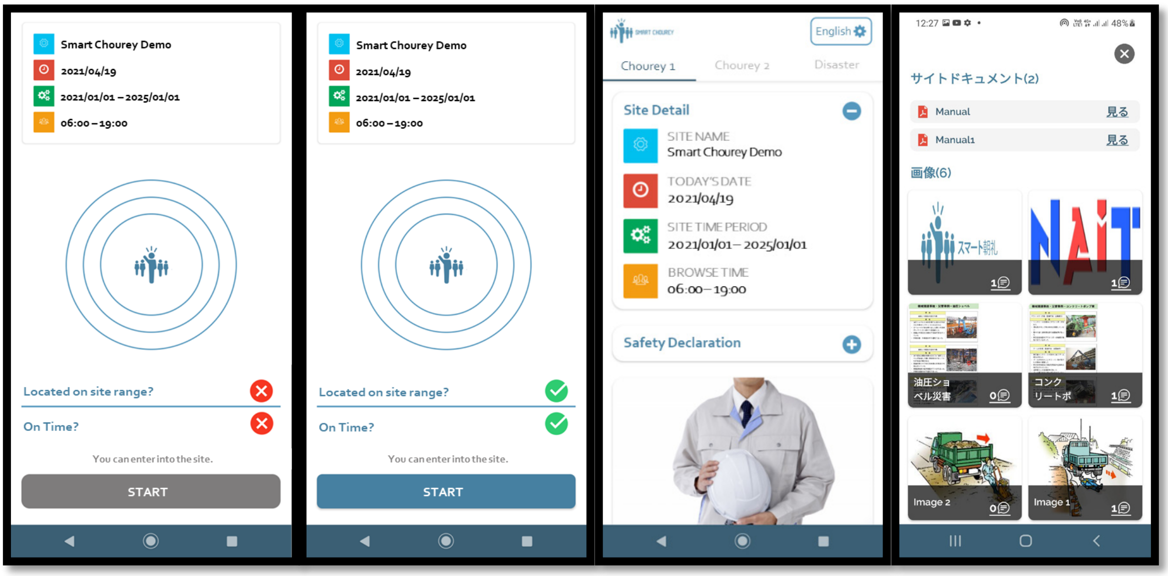


Fig.4. Manager screen to enter the site information and site address for GPS allocation.

For GPS location, Android OS provides default framework called “Location”, which can be used to track the geolocation of the user [14]. This geo location is first used to verify if the worker and the worker’s registered smartphone has entered the site range or not. Once the initial identification and authorization is completed, the application continues to check distance between the site and the workers device. The device will also check the designated access time set by the site manager. The visibility of data on the app is controlled based on the device's current distance from the centre of the site, designated time with data access being limited if the device is outside of the defined location and time range.

The image showing the screen of the application while checking the time range, GPS range is shown in figure 5a, 5b and 5c. In figure 5a, the device is not inside the GPS range and time range which is indicated by the red × mark. The start button is not activated in this case. In figure 5b, the device satisfies the GPS and time range condition with green✓ mark and the start button is activated. Once the user clicks the start button, the user can get access to the site information as shown in figure 5c, and access to videos, images and PDF files is shown in Fig. 5d.



(a) (b) (c) (d)

Fig.5. (a) Application screen showing the device is not located on site range and Time. (b) Application screen showing the device is within site range and time. (c) Application Home screen with site information.(d) Video and Image screen.

3.2. Working Flow of the Novel application

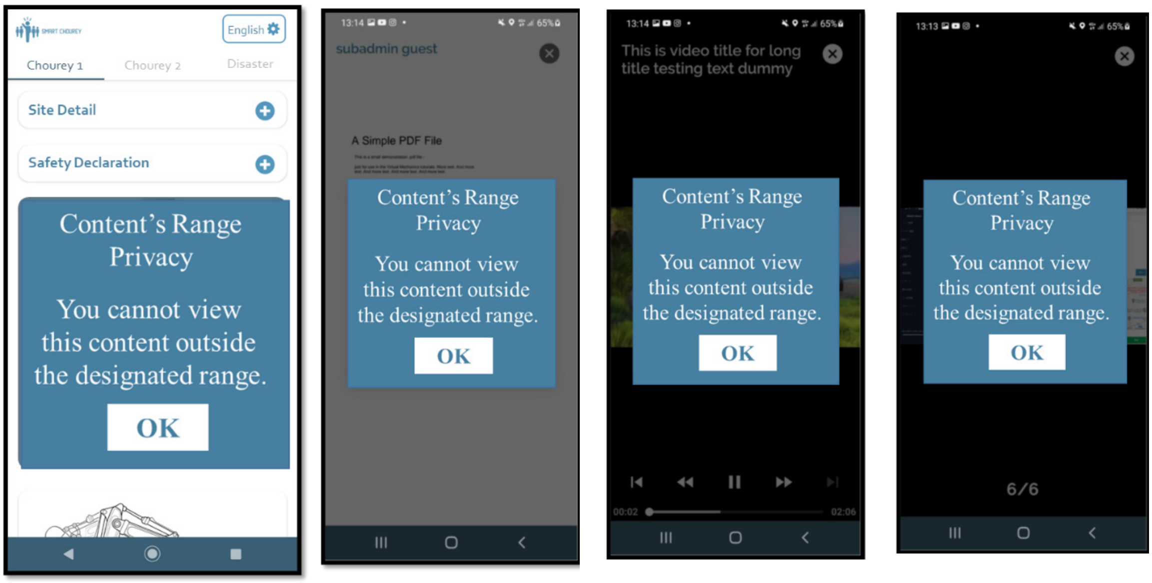
The working flow of the novel application is as follows.

1. *Initialize the GPS on the worker's device and start monitoring the location.*
2. *Verify if the worker's device has entered the site's location by comparing the device's location to the defined site location.*
3. *If the device is within the site's location at designated time period, let the user of the application i.e. the worker use the app and access the information. If not, don't display the information.*
4. *Continuously calculate the distance between the device's current location and the defined center point of the site* [15].
    1. *Initialize two objects of the "Location" class and store the latitude and longitude values of the two locations.*
    2. *Calculate the distance between the two locations using the "distance to" method of the "Location" class.*
    3. *Format the result of the calculation as a double value with two decimal places and return the final result.*
5. *Compare the calculated distance to the designated site access range.*
6. *If the distance exceeds 1 meter, display an error, and stop broadcasting the site related information.*
7. *Repeat steps 4-6 until the worker's device is within the designated site access range within designated time.*

4. Security and UI/UX Features

The novel application is user friendly and highly have security features to prevent from data leakage, site Privacy and user privacy. The system is highly user friendly for the targeted user who are construction workers. In our novel application, the users don't have to open the browser, enter login info, read the QR code etc. Instead, the user can just open the application and the system automatically checks the location of the device using the GPS allocation system and the user can directly get access to the site information. The site access time is automatically saved in the server and can be used as an attendance system.

The above-mentioned feature reflects not only the user-friendly part, but also the security part. This feature avoids unauthorized access to the site information because the device needs to be mapped with the designated site with the help of IT administrator. Similarly, the manager can set the the browse range for every site information contents, so that the contents can be made visible only in the designated areas. The image showing the restriction of the content's visibility is shown in Fig. 6.



(a) (b) (c) (d)

Fig.6. Screen showing the contents range privacy on (a) Feed details. (b)PDF Reader. (c) Video Player. (d) Image viewer

This application can be used in the non-GPS environment like tunnels and undergrounds where there is no GPS signal [16]. To use this application in such places, the user must open the application and get access to the site at first in the GPS environment area. When the user moves to the non-GPS environment, the IMU device of the system is activated and calculates the range of the device and make contents visible to the user even in the non-GPS environment [17]. This tool reflects the novelty of our system.

5. Testing and Evaluation

We tested the novel application daily in multiple construction sites for more than a year. The sites are depending only on our novel application for conducting morning assembly on sites. The Physical style of morning assembly system have been changed to the digital way. The novel application has changed the old style of morning assembly to the modern digital style. While using our previous application, the sites used to conduct morning assembly on site physically as well as register the information on the application.

This novel application collects the logs and data of all the registered devices mapped with the sites. The application also collects the access of the users on the sites. The aggregated data is saved in a database. This database can be used to identify who has accessed the site and who has checked the safety declaration site wise. The novel application was tested in the construction sites by the construction workers and the workers were fully satisfied with the novel application compared to the previous application.

We evaluated the novel application in the construction sites, and we have generated a data showing the user access report. To compare the access of the novel and previous application, we tested our applications in a construction site with 550 workers for 12 months. For the first 6 months, we used our previous application, the user access graph is shown in Fig.7. The user access rate increased from 35% to 72% with continuous announcement for using the application. Similarly, for the next 6 months, we used our novel application, and the user access graph is shown in Fig.8. The user access rate increased from 73% to 99%. The physical morning assembly was stopped in this site with this user access result. We also took an interview with the site managers regarding the usage of morning assembly application and received the comments stating the reduction of time and effort required for preparing the morning assembly contents.

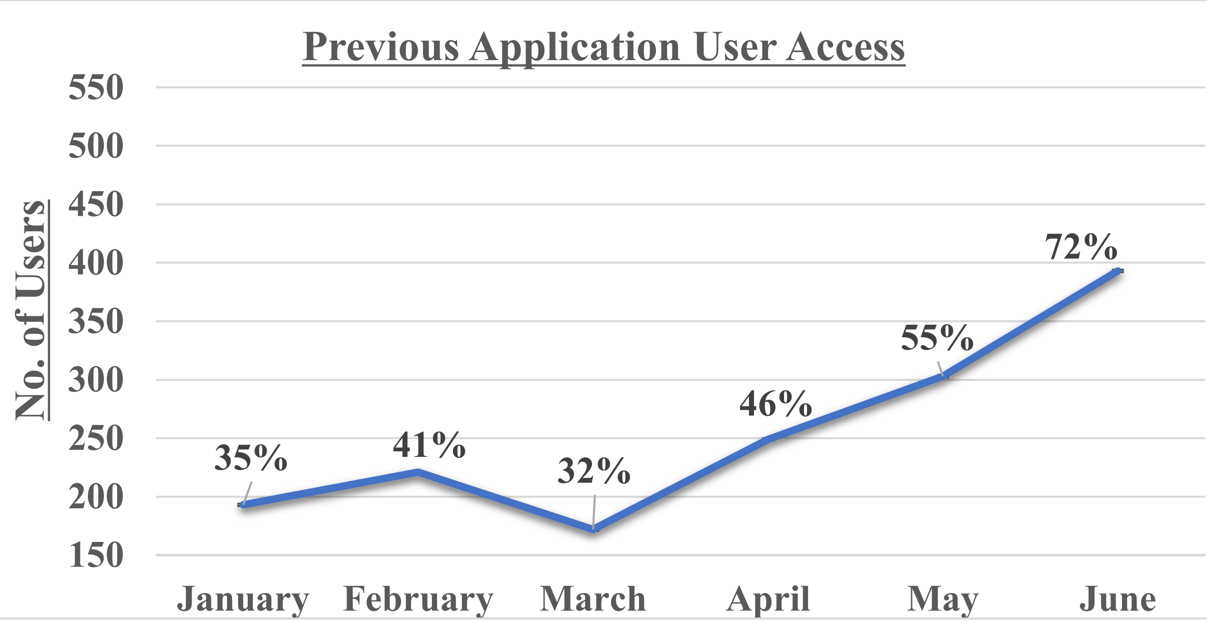


Fig.7. Graph showing the user access report of our previous application.

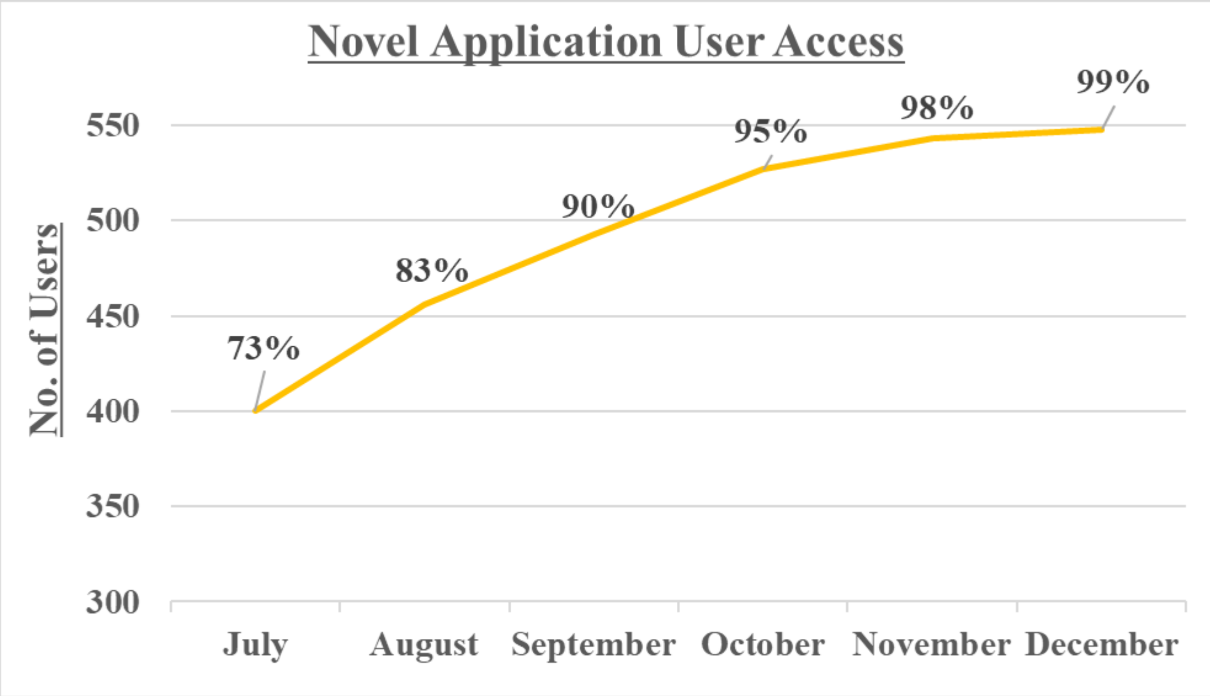


Fig.8. Graph showing the user access report of our novel application.

6. Discussion & Conclusion

In conclusion, the novel application for conducting morning assembly in construction sites in Japan has worked as intended. The traditional approach of crowded and unmanaged assemblies has been replaced with a decentralized and secure method of information dissemination, using the GPS location of the site and the registered worker's smartphone as an identification pair. The application has a simple yet intuitive UI/UX design, which addresses the issue of workers' IT illiteracy. The application has been tested in multiple construction sites and has helped to increase the productivity of managers and workers significantly. The application has been developed in such a way that, it is highly secured for avoiding the unauthorized access, data leakage of the sites and the privacy of the users. Several sites have stopped performing the Physical assembly in the sites and have changed into the digital way of performing the morning assembly which results in the saving of time for both workers and the managers. Which results in the productivity improvement of the construction sites. Furthermore, it reduces the risk of spreading infectious diseases like COVID-19 and others. Overall, the proposed application has proven to be an effective solution for managing morning assembly in construction sites in Japan and sharing the site information to the construction workers in a simplest way.

References

[1] B. Lamsal, M. Oka, B. Kumar Kc, and N. Kojima, "A Mobile-based Application for Performing Assembly on the Construction Sites in a Decentralized Manner," Proceedings of the Creative Construction e-Conference 2022, 2022, doi: 10.3311/ccc2022-007.
[2] M. Golparvar-Fard, P. Tang, Y. K. Cho, and M. K. Siddiqui, "Grand Challenges in Data and Information Visualization for the Architecture, Engineering, Construction, and Facility Management Industries," Computing in Civil Engineering, Jun. 2013, doi: 10.1061/9780784413029.106.
[3] C. Z. Li, Z. Guo, D. Su, B. Xiao, and V. W. Y. Tam, "The Application of Advanced Information Technologies in Civil Infrastructure Construction and Maintenance," Sustainability, vol. 14, no. 13, p. 7761, Jun. 2022, doi: 10.3390/su14137761.
[4] S. Majumder and D. Biswas, "COVID-19 Impacts Construction Industry: Now, then and Future," Lecture Notes on Data Engineering and Communications Technologies, pp. 115–125, Dec. 2020, doi: 10.1007/978-981-15-9682-7_13.
[5] M. M. Din and A. Fazal Fazla, "Integration of Web-Based and Mobile Application with QR Code implementation for the library management system," Journal of Physics: Conference Series, vol. 1860, no. 1, p. 012018, Mar. 2021, doi: 10.1088/1742-6596/1860/1/012018.
[6] R. S. Vasilyev, K. Y. Losev, A. G. Cheprasov, and D. T. Bektash, "BIM and QR-codes interaction on a construction site," Journal of Physics: Conference Series, vol. 1425, no. 1, p. 012089, Dec. 2019, doi: 10.1088/1742-6596/1425/1/012089.
[7] https://www.behance.net/gallery/79428911/Jobsite-Construction-Management-UX-Case-Study.
[8] A. S. Rao et al., "Real-time monitoring of construction sites: Sensors, methods, and applications," Automation in Construction, vol. 136, p. 104099, Apr. 2022, doi: 10.1016/j.autcon.2021.104099.
[9] C. Kim, T. Park, H. Lim, and H. Kim, "On-site construction management using mobile computing technology," Automation in Construction, vol. 35, pp. 415–423, Nov. 2013, doi: 10.1016/j.autcon.2013.05.027.
[10] K. Tabata, M. Nakajima, and N. Kohtake, "Design of Entry Detection Method for Top-Bounded Spaces Using GPS SNR and Spatial Characteristics for Seamless Positioning in Logistics Facilities," Sensors, vol. 20, no. 23, p. 6864, Nov. 2020, doi: 10.3390/s20236864.
[11] L. Nie, K. S. Said, L. Ma, Y. Zheng, and Y. Zhao, "A systematic mapping study for graphical user interface testing on mobile apps," IET Software, Mar. 2023, doi: 10.1049/sfw2.12123.
[12] G. Svennerberg, "Introducing the Google Maps API," Beginning Google Maps API 3, pp. 1–6, 2010, doi: 10.1007/978-1-4302-2803-5_1.
[13] M. Singhal and A. Shukla, " Implementation of Location based Services in Android using GPS and Web Services," International Journal of Computer Science Issues, vol. 9, no. 1, p. 237-242, Jan. 2012
[14] Y. Shavitt and N. Zilberman, "A Geolocation Databases Study," IEEE Journal on Selected Areas in Communications, vol. 29, no. 10, pp. 2044–2056, Dec. 2011, doi: 10.1109/jsac.2011.111214.
[15] " Calculating the Distance between Two Inaccessible Points," Wolfram Demonstrations Project, Feb. 2008, doi: 10.3840/002717.
[16] H. Huang and G. Gartner, "Current Trends and Challenges in Location-Based Services," ISPRS International Journal of Geo-Information, vol. 7, no. 6, p. 199, May 2018, doi: 10.3390/ijgi7060199.
[17] Wahyudi, M. S. Listiyana, Sudjadi, and Ngatelan, "Tracking Object based on GPS and IMU Sensor," 2018 5th International Conference on Information Technology, Computer, and Electrical Engineering (ICITACEE), Sep. 2018, doi: 10.1109/icitacee.2018.8576928.

AN ASSEMBLED AND INTERLOCKING LUNAR BASE AND ITS STRUCTURAL ANALYSIS

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Abstract

Establishing a base on the lunar surface has become a new goal for space powers and even all humankind to explore the moon. However, the extreme environment and the lack of resources pose many challenges to the construction project. In this paper, an assembled and interlocking mixed structure was designed. The sintered lunar regolith can be used to build the load-bearing arch structure and the foundation structure, which are assembled by interlocking modules to facilitate construction on the lunar surface. An independent inflatable structure is needed inside the arch structure to ensure the air pressure environment suitable for human survival. The structure is covered with a 3m-thick lunar regolith layer to withstand large temperature fluctuations, intense radiation, and occasional micrometeorite impact. The main mechanical advantage of this structure is that each component is used to bear the load that it is best able to resist. The load-bearing arch structure and the foundation structure can be assembled and constructed with only 6 types of modules. Besides, the modules are self-supporting so that they can be assembled without support during construction. Subsequently, the finite element method was used to analyze the stress state after construction. The results showed that this lunar base structure is feasible, but the optimization design needs to be carried out at the module joint because it will produce stress concentration. This study provides a scheme for the construction of human lunar bases.

Peer-review under responsibility of the scientific committee of the Creative Construction Conference 2023.

Keywords: finite element method, interlocking arch structure, lunar base, structural analysis.

1. Introduction

The Moon is the nearest extraterrestrial body to the Earth, and also the advance station of human exploration of space. Many countries are actively exploring the Moon and are committed to building lunar bases. The existence of a lunar base will facilitate human's in-depth exploration on the Moon, including resource exploitation and scientific research. The lunar base will include habitat, landing pads, roads, energy stations and other infrastructure. Due to the high cost of transporting construction materials from the Earth, in-situ resource utilization (ISRU) will be the sustainable development direction of lunar surface construction projects in the future.

Given its abundance and availability, lunar regolith is considered a potential resource for in-site production of building materials on the Moon. Many methods of treating lunar regolith have been proposed, such as melting, sintering, and binding with additives. Sintering is one of the most promising technologies because it does not require any additives. Many studies have been conducted on the feasibility of various sintering technologies, including furnace sintering [1], laser sintering [2, 3], microwave sintering [4-6], and solar sintering [7].

Although the lunar regolith can be used in situ for construction, the cost of processing it into building materials is also very high. Therefore, the reasonable design and optimization of the building structure is also very important to save building materials and reduce the resource consumption of the building project.

2. Structural design

Different types of lunar bases, including inflatable [8], rigid [9, 10], and mixed structures [11-14], have been proposed over the years. Inflatable structures must be carried from the Earth and have good gas tightness and excellent ability to withstand internal pressure. Rigid structures could be built in situ using lunar regolith, eliminating the need to carry building materials from the Earth. The mixed structure is a combination of these two structural forms and has the advantages of both.

The construction scheme proposed in this study is based on the assumption that sintered lunar regolith is used as building material, so the physical and mechanical properties of sintered lunar regolith should be fully considered, and the structural form that conforms to its mechanical characteristics should be designed.

1. The tensile strength of the sintered lunar regolith was much lower than the compressive strength. Hence, buildings constructed from sintered lunar regolith should be designed as structural forms mainly used to withstand compressive stress, such as arches and domes.

2. Lunar regolith sintering requires the use of molds, which need to be carried from Earth. Therefore, construction components should be modular, and the types of modules should be minimized. The modules need to be interlocked to ensure the high reliability of the structure.

Interlocking assembly structures have been proposed for lunar bases, including habitats [13, 14], lunar landing pads [15, 16], and more. An assembled and interlocking mixed structure was designed according to the above suggestions, as shown in Fig. 1. The sintered lunar regolith was used to build the load-bearing arch structure and the foundation structure, which were assembled by interlocking modules to facilitate construction on the lunar surface. The interlocking foundation structure had an excellent bearing capacity. The load-bearing arch was covered with a compacted lunar regolith layer with a thickness of 3.0 m to withstand high-frequency meteorite impacts, large temperature differences, and heavy radiation. An independent inflatable structure was needed inside the arch structure to ensure an air pressure environment suitable for human survival. The main mechanical advantage of this structure was that each component was used to address the challenge that it was best able to resist. This division of the different mechanical tasks reduced the complexity of the internal force systems, which consequently made the structural behavior safer.

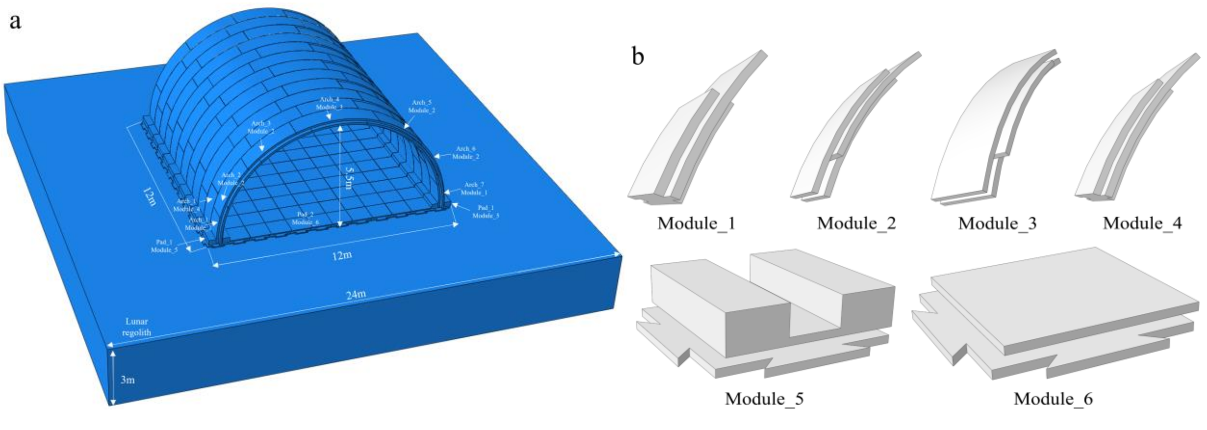

Fig. 1. (a) Structural scheme of arch structure and foundation structure of the lunar base, (b) interlocking assembly modules.

3. Finite element model

The finite element software ABAQUS was used for modeling and static analysis of the lunar base under the self-weight and overburden pressure induced by the lunar regolith layer. The inflatable structure was not considered in the model because it is independent of the arch-regolith system. The finite element model is shown in Fig. 2. The mechanical properties of the samples sintered at 1040 °C were adopted as the material properties of the arch structure and foundation structure, and the Drucker-Prager Cap plasticity model was employed to represent the lunar regolith that exhibits frictional properties. Table 1 summarizes the bulk density and shear strength used in this material model. Table 2 lists the lunar soil model properties that were consistent for all layers.

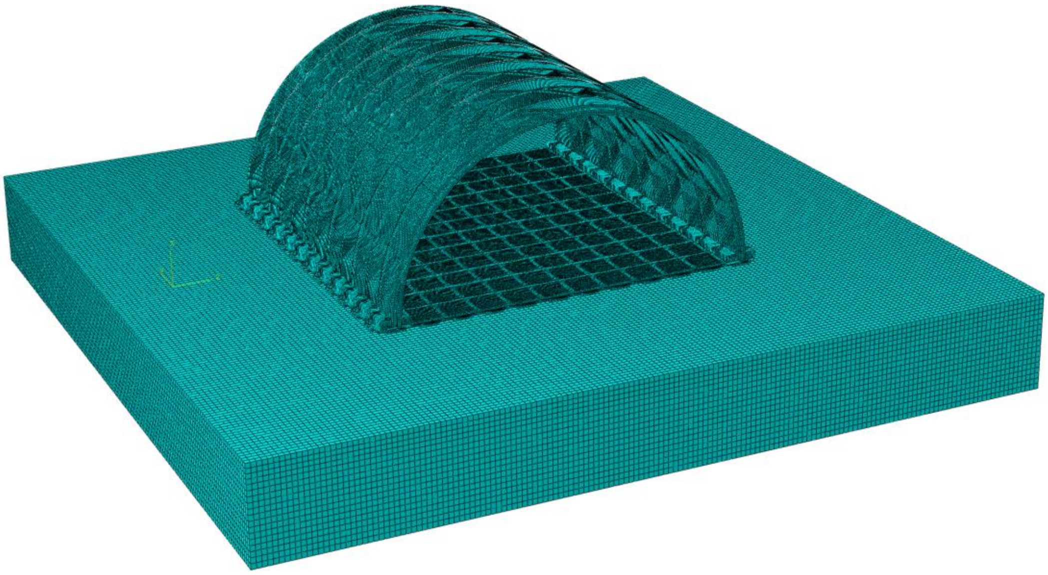

Fig. 2. Finite element model of the proposed lunar base structure and regolith basement.

Table 1. Bulk density and shear strength parameters of lunar regolith model layers.

Depth Range (cm)	Bulk Density ρ (g/cm^3)	Cohesion d (kPa)	Internal friction angle β (degrees)
0-30	1.58	1.01	49.2
30-60	1.74	2.78	51.9
>60	1.80	2.78	51.9

Table 2. Lunar regolith model properties.

Elastic	Young's modulus E (MPa)	182
	Poisson ratio ν (-)	0.28
Cap plasticity	Cap Eccentricity Parameter R (-)	0.4
	Initial Cap Yield Surface Position ε_0 (-)	0
	Transition Surface Radius Parameter α (-)	0.05
	Flow Stress Ratio K (-)	1

For static analysis, the self-weight of the lunar base and the overburden pressure induced by the lunar regolith layer were considered. As Table 1 shows, the density of lunar regolith is 1.80 g/cm^3 when the depth is greater than 60 cm. The overburden pressure induced by the lunar regolith layer over the arch structure can be calculated as:

$$P = \rho \times g_l \times h = 1800 kg/m^3 \times 1.63 m/s^2 \times 3m = 8818 \boldsymbol{k} Pa \quad (1)$$

where g_l is the gravity on the moon, and ρ and h are the density and thickness of the lunar regolith layer, respectively.

4. Results and discussion

The vertical deformation and principal stress contours are illustrated in Fig. 3 and 4, respectively. Considering that the proposed lunar habitation is a prefabricated structure, the principal tensile stress governs structural safety. As shown in Fig. 4, the arch modules located on both ends receive higher maximum principal stresses compared to the arch modules located in the middle position. The maximum principal tensile stress of Arch_1 was 59.45 MPa, and the maximum principal tensile stress of Arch_5 was only 11.27 MPa. Thus, the arch modules located on both ends should be thicker or use materials with higher tensile strength. The middle arch modules can be designed to be thinner. Moreover, the stress was mainly concentrated in the interlocking parts of the arch modules, which means that the interlocking parts should be specially designed to reduce the stress concentration.

The maximum principal tensile stress received by the foundation modules was much higher than that of the arch modules, which indicated that the foundation structure should be made of materials with higher tensile strength. In addition, the stress was mainly concentrated in the interlocking parts of the foundation modules, and the maximum principal tensile stress for Pad_1 was as high as 400.4 MPa. Thus, the interlocking parts should be specially designed to reduce the stress concentration or use a larger foundation structure.

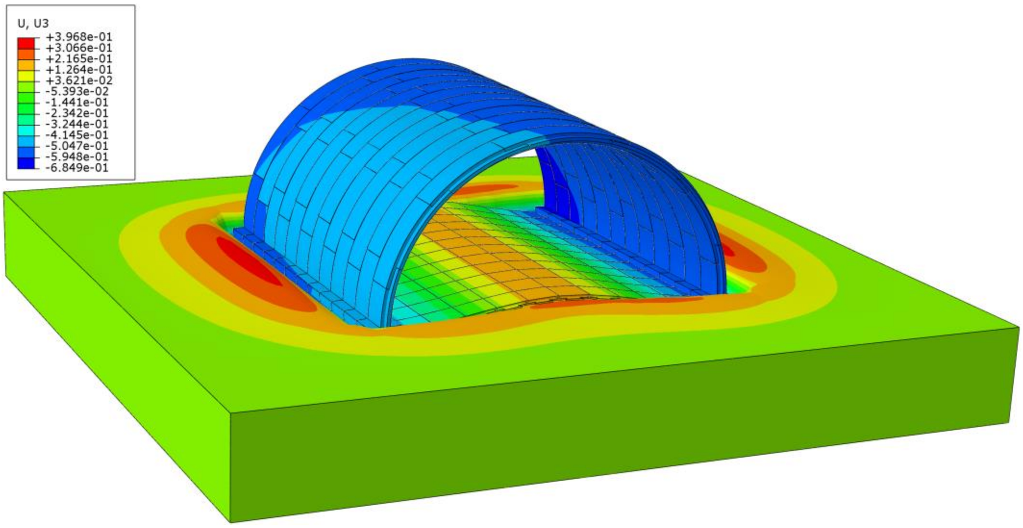

Fig. 3. Vertical deformation fields for the lunar base.

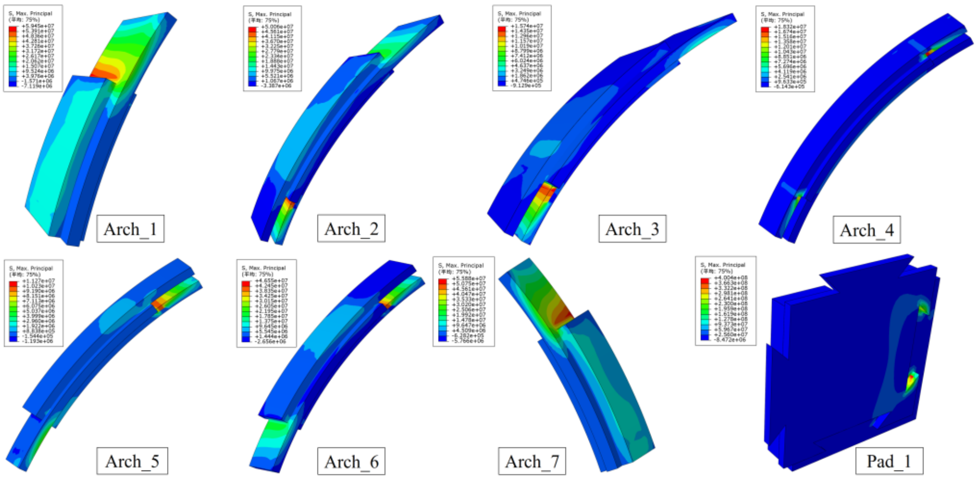

Fig. 4. Maximum principal stress of the arch modules and foundation modules.

5. Conclusion

In summary, this study proposes an assembled and interlocking mixed lunar base structure, which can be assembled by 6 types of modules. The finite element method was used to model this structure, and the interaction between modules was considered. The stress state of the structure under the self-weight and overburden pressure induced by the lunar regolith layer was analyzed, and the following conclusions were obtained:

(1) The module is prone to produce large stress concentration at the joint, which should be avoided by optimizing the design of the joint;

(2) The stress of the arch modules located on both ends is higher and should be designed for thicker structure;

(3) The tensile stress of the bottom plate structure is very high, so thicker structure design or other ways should be adopted to improve its performance of bearing tensile stress.

The maximum principal tensile stress received by the foundation modules was much higher than that of the arch modules, which indicated that the foundation structure should be made of materials with higher tensile strength. In addition, the stress was mainly concentrated in the interlocking parts of the foundation modules, and the maximum principal tensile stress for Pad_1 was as high as 400.4 MPa. Thus, the interlocking parts should be specially designed to reduce the stress concentration or use a larger foundation structure.

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References

[1] W. Han, L. Ding, L. Cai, J. Zhu, H. Luo, and T. Tang, "Sintering of HUST-1 lunar regolith simulant," Construction and Building Materials, Article vol. 324, 2022, Art no. 126655, doi: 10.1016/j.conbuildmat.2022.126655.

[2] L. Caprio, A. G. Demir, B. Previtali, and B. M. Colosimo, "Determining the feasible conditions for processing lunar regolith simulant via laser powder bed fusion," Additive Manufacturing, Article vol. 32, 2020, Art no. 101029, doi: 10.1016/j.addma.2019.101029.

[3] K. W. Farries, P. Visintin, and S. T. Smith, "Direct laser sintering for lunar dust control: An experimental study of the effect of simulant mineralogy and process parameters on product strength and scalability," Construction and Building Materials, Article vol. 354, 2022, Art no. 129191, doi: 10.1016/j.conbuildmat.2022.129191.

[4] S. Allan, J. Braunstein, I. Baranova, N. Vandervoort, M. Fall, and H. Shulman, "Computational modeling and experimental microwave processing of JSC-1A lunar simulant," Journal of Aerospace Engineering, Article vol. 26, no. 1, pp. 143-151, 2013, doi: 10.1061/(ASCE)AS.1943-5525.0000245.

[5] Y. J. Kim, B. H. Ryu, H. Jin, J. Lee, and H. S. Shin, "Microstructural, mechanical, and thermal properties of microwave-sintered KLS-1 lunar regolith simulant," Ceramics International, Article vol. 47, no. 19, pp. 26891-26897, 2021, doi: 10.1016/j.ceramint.2021.06.098.

[6] L. A. Taylor and T. T. Meek, "Microwave sintering of lunar soil: Properties, theory, and practice," Journal of Aerospace Engineering, Article vol. 18, no. 3, pp. 188-196, 2005, doi: 10.1061/(ASCE)0893-1321(2005)18:3(188).

[7] A. Meurisse, A. Makaya, C. Willsch, and M. Sperl, "Solar 3D printing of lunar regolith," Acta Astronautica, Article vol. 152, pp. 800-810, 2018, doi: 10.1016/j.actaastro.2018.06.063.

[8] P. S. Nowak, W. Z. Sadeh, and L. A. Morroni, "Geometric modeling of inflatable structures for lunar base," Journal of Aerospace Engineering, Article vol. 5, no. 3, pp. 311-322, 1992, doi: 10.1061/(ASCE)0893-1321(1992)5:3(311).

[9] S. Mottaghi and H. Benaroya, "Design of a lunar surface structure. I: Design configuration and thermal analysis," J Aerospace Eng, Article vol. 28, no. 1, 2015, Art no. 04014052, doi: 10.1061/(ASCE)AS.1943-5525.0000382.

[10] S. Mottaghi and H. Benaroya, "Design of a lunar surface structure. II: Seismic structural analysis," J Aerospace Eng, Article vol. 28, no. 1, 2015, Art no. 04014053, doi: 10.1061/(ASCE)AS.1943-5525.0000396.

[11] G. Cesaretti, E. Dini, X. De Kestelier, V. Colla, and L. Pambaguian, "Building components for an outpost on the Lunar soil by means of a novel 3D printing technology," Acta Astronautica, Article vol. 93, pp. 430-450, 2014, doi: 10.1016/j.actaastro.2013.07.034.

[12] T. Rousek, K. Eriksson, and O. Doule, "SinterHab," Acta Astronautica, Article vol. 74, pp. 98-111, 2012, doi: 10.1016/j.actaastro.2011.10.009.

[13] C. Zhou et al., "In-situ construction method for lunar habitation: Chinese Super Mason," Automation in Construction, Article vol. 104, pp. 66-79, 2019, doi: 10.1016/j.autcon.2019.03.024.

[14] C. Zhou, B. Tang, L. Ding, P. Sekula, Y. Zhou, and Z. Zhang, "Design and automated assembly of Planetary LEGO Brick for lunar in-situ construction," Automation in Construction, Article vol. 118, 2020, Art no. 103282, doi: 10.1016/j.autcon.2020.103282.

[15] W. Han, C. Zhang, J. Sun, C. Zhou, and L. Ding, "Experimental and numerical study on the structural behavior of assembled interlocking lunar landing pad," Acta Astronautica, vol. 207, pp. 77-88, 2023/06/01/ 2023, doi: https://doi.org/10.1016/j.actaastro.2023.03.001.

[16] A. V. Dyskin, Y. Estrin, E. Pasternak, H. C. Khor, and A. J. Kanel-Belov, "The principle of topological interlocking in extraterrestrial construction," Acta Astronautica, Article vol. 57, no. 1, pp. 10-21, 2005, doi: 10.1016/j.actaastro.2004.12.005.

ANALYSIS AND MEASURES TO IMPROVE THE EFFICIENCY OF BUILDING INFORMATION MODELLING IN COST ESTIMATES

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Abstract
Building Information Models (BIM) and information in these models have been responsible for an "industrial revolution" in the construction industry, but there has not been the same focus on BIM in the early stages of planning, such as using it in cost estimation and calculations, also called 5D-BIM. Our research question is: “What are the advantages and disadvantages of using BIM in the estimation phase, and which measures can make this more efficient and user friendly.” Information was first obtained by examining cost estimation programs used in a larger construction company in Norway. Secondly a survey was sent out to employees in the construction industry, where the respondents were asked to assess and explain their relationship with BIM and cost estimation. The results revealed that there is a lack of competence and training for those who use BIM-models for cost estimation. Secondly It has been identified that BIM-models used to calculations is not detailed enough. Integration of cost estimation earlier in the project development would have more influence on choices and solutions. The conclusion is that cost estimation has to be more efficient in the interaction with BIM, including implementation of stricter requirements for BIM-models used for dynamic calculations, skills need to be raised, calculations should be involved earlier in the projects, and the public sector should be involved more to propose measures.

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Keywords: Building Information Modelling, Cost estimates and Calculations.

1. Introduction

Norway is among the pioneers in the use of BIM tools. Attention is drawn to the fact that Norway also has its challenges with the use of BIM tools. It is pointed out that contractors have a lot to gain by working smarter and in close cooperation with other players in the industry [1]. In Norway, BIM-implementation has been in progress for many years, much due to Statsbygg, one of the largest construction developers in Norway, demanding BIM since 2010 [2]. Therefore, many of the large architecture, engineering and construction (AEC) firms operating in Norway have hands-on experience in working with BIM [3]. In Norway there is a national standard, NS 8360:2015 for BIM-objects [4], that has been important for the implementation of BIM in new buildings. Models and information in these models have been responsible for an "industrial revolution" in the construction industry, but there has not been a focus on BIM in the early planning phase to the same extent as the use of BIM models on construction sites. Although the use of BIM in calculations of buildings has lagged behind, there has also been an evolution there. This paper examines and identifies the current challenges, disadvantages and advantages of using BIM in the early phase of a project, mainly cost estimation, and then identifies measures that can be taken based on feedback from a survey. This paper has, thereby, chosen to take a step further and look at digitization with the help of the transfer of data from the BIM-model to calculation programs, to see how it is expected to affect work in the cost estimation of buildings in Norway. The research question is: *What are the advantages and disadvantages of using BIM in the estimation phase, and what measures can make this more efficient and user friendly.* The purpose is to see to what extent today’s BIM technology is expected to have an impact on productivity in a calculation process, and whether this might simplify or complicate the work.

2. Theory

McKinsey & Company published a report in 2020 that described the future of the construction industry from a technological perspective. We are in the middle of a divide where many software solutions have been implemented, which gained momentum during the Covid pandemic [5]; however, many people still use Excel and software that is not explicitly intended for calculation for civil engineering projects. In this transition phase where you slowly but surely move to dedicated calculation programs, it is natural that there will be a period of adaptation for both end user and developer. The developers must work to make their software user-friendly, while users must be trained and accustomed to new methods. For the interests of this paper it is necessary to describe some of the programs used in the case study.

2.1. Solibri

With Solibri you can collect, check and quality-assure your BIM projects. The tool helps you maintain the required quality in models from different disciplines, so that all parties involved can work together effectively [6]. Solibri could also be used to quantity take-offs.

2.2. Naviate Simple BIM

Naviate Simple BIM is a BIM editing program that is used to create models that contain the exact information needed. The model is trimmed and edited to contain information that is relevant. It is then exported as an IFC file that is used as needed. Another advantage that comes with this is that the file size becomes smaller when unnecessary information is eliminated from the file. This can be anything from aesthetic illustrations such as furniture to entire buildings that are not to be included. You can, for example, trim away everything and be left with the building structure and information relevant to this only [7].

2.3. ISY ByggOffice

ISY ByggOffice from Norconsult Information Systems is an online program used in the estimation phase to calculate all types of projects. On its website, the calculator tab is described as a program that is organized and efficient and has ease of use in focus [8]. It also has the ability to store empirical values in the form of unit times and resource consumption. This makes cost estimation more accurate, and you can update these figures as often as you like. ISY ByggOffice also has the option of importing BIM models for taking off quantities and objects. This of course assumes that the model is accurate and tidy. When the model is in the required condition and imported, you then get a complete calculation description.

3. Method

Information was first obtained by examining cost estimation programs used in a large construction company in Norway. A case study was done using the BIM-architect model of an apartment building in Oslo, Norway. The BIM model, made by the architect, was transferred to Solibri and Simple BIM. After some revision and simplifying of the BIM model, it was transferred to ISY ByggOffice which was the calculation program used.

Secondly a survey was sent out to 30 employees in the construction industry. 17 people in the construction industry answered these questions, this group consisted of 9 project leaders/ project engineers, 3 BIM-designers, 1 building designer and 4 calculation specialists. The respondents were asked to assess and explain their relationship with BIM and cost estimation. The questions were divided into three parts. First they focused on the use of BIM-tools, next they focused on calculation tools, and finally they focused on the correlation between BIM and calculation tools. The analysis of the results follows the questions asked and the results are discussed. The responses were obtained and analysed from a qualitative perspective and assessed against the use of these programs through participatory observation and experiences.

4. Results

The results are divided into two parts. Firstly they focus on examining cost estimation programs used in a larger construction company in Norway using a case study. Secondly they focus on the survey that was sent out to employees in the construction industry.

4.1. Examining of cost estimation programs used in an apartment building case in a larger construction company in Norway.

The examination of cost estimation in a construction company in Norway revealed that BIM-models have been used in all newer projects. There is a varying degree of information and accuracy in these models, some lack important information necessary for the calculations. There have been projects with, for example, doors that lack requirements for fire resistance. Also duplicates of objects occur, which increases the cost of the project and can lead to double orders if not discovered in the final design phase.

Fig. 1. The case study using one of these apartment buildings in Oslo, Norway [9].

The case study using an apartment building, revealed that there are great advantages of using a model trimmer such as Simple BIM to simplify the BIM-model before the calculation process. The model is trimmed so that it takes up less space and smaller elements, which leads to less storage space being used and thus also less RAM memory to run the model on a PC. The disadvantage with this is that it is time-consuming. In addition to this, training, skills development and familiarization are required to make it effective. One must also be aware that such software licenses cost a great deal of money for companies, and when you have to use several different softwares, the expenses also increase both in the form of license fees and courses/training of the designers.

It seems that a recurring problem is the fact that a model is not fully developed and all solutions are not fully designed by the time the calculation is made. Often, documents received have been changed during a tender. An example that repeats itself is to replace site-built bathrooms with cabin solutions that are installed in the building with taps and connected to the water and electricity network.

With the extraction of information from a window in the program Solibri, the ID numbers of the windows was missing, then the window form could not be taken out and sent to contractors and providers. No sound and fire requirements had been entered either. This had to be implemented manually from the reports from the sound and fire engineering consultants. Loots of time was used to put the right information into the BIM-model before transferring it to ISY Byggofice.

4.2. Results of the survey sent out to the employees in the construction industry in Norway.

There were 17 responses on the survey,16 (94,1 %) of them had experience with the use of BIM tools and 14 (82,4 %) had experience with the use of cost calculation programs.

Of the 16 with experience of BIM-tools, 16 had experience with the use of Solibri, 7 had experience with the use of Archicad, 7 had the experience with the use of Revit, and 4 had experience with the use of SimpleBIM, (see figure 1a). Other programs used were Autocad, Tekla Structure, Interaxo fields, StreamBIM and Allplan.

Of the 14 with experience of calculation programs, 10 had experience with the use of ISY ByggOffice, 12 had experience with the use of Excel, and 4 had experience with the use of Geometra, (see figure 1b). Other programs used was Holte SmartKalk, ISY Linker, ISY Beskrivelse, Bluebeam, Revit MEP, ISY G-prog and Focus Anbud. The answers that came back were not surprising; Solibri, ISY ByggOffice and Excel still run the show.

a b

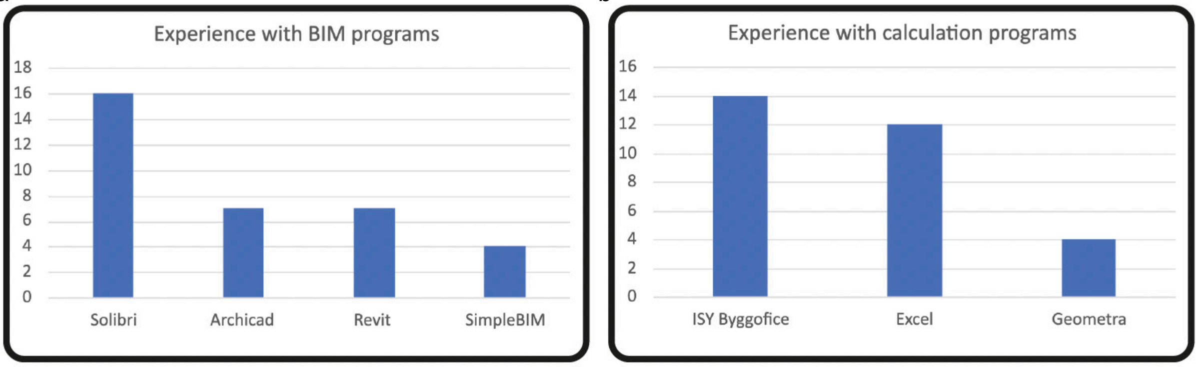

Fig. 1. (a) Respondents experience with BIM-programs; (b) Respondents experience with calculation programs.

After identifying users of BIM and calculation tools, the next step was to find out how satisfied these users were with the interaction between BIM and calculation programs. A majority of 41% stated a satisfaction level of 6 on a scale between 0 and 10, were 10 was the best. There were also some users who stated higher and lower, but no one had stated a degree of satisfaction higher than 8. There were some users who were quite unhappy as well. Taken together, the average was 5.53 and the median was 6.

An answer often repeated among the respondents, is that the models in the early phase are not detailed or complete enough to perform accurate calculations and cost estimates. As one of the participants in the survey points out: *"Models this early in the phase are not good enough to provide a full basis for calculations. But it visualizes the building and you get a better understanding of what is to be built."* Another answer gives a similar picture: "*The BIM model is often not complete enough to be used as a calculation tool, but can be used as a visual understanding*".

The respondents then answered what advantages there were with the use of BIM tools in the early calculation/ planning phase. An answer repeated often, was that it makes the project visual and holistic. This in turn makes it easier to identify pitfalls and often forgotten elements. Other arguments are that it is time-saving and easier to identify collisions using a BIM model.

The respondents were also asked about the disadvantages of using BIM tools in the calculation/planning phase. The results show that BIM models from architects and consultant engineers are not detailed enough and contain errors, and models used for calculations do not necessary represent what is being built. It is also a recurring theme that competence is inadequate and that this needs to be addressed. One respondent summed it up like this: *"Too much trust in models often leads to tunnel vision. It must be used correctly, and one must have the competence to see the details that do not appear in the model."*

Then the respondents were asked what they actually needed to use from the BIM-models in calculations or preliminary projects. The answers were slightly more varied. One of the answers was that ISY ByggOffice was too messy to use, with a desire to switch to a setup on Excel, another answer was that you should create a standard for the model before you switch to a calculation phase. An interesting response that was obtained was as follows: *“Want more use of dynamic calculation. That we get to the point where calculation is more of a natural part of the preliminary, sketch, detail and execution project phases. More of a natural part of the planning in these phases (and operations administration in the latter)”.*

Finally, the respondents were asked about their point of view on the industry's relationship with BIM in calculations / preliminary projects. There were many answers, but a common denominator in the answers was that further development and adoption of BIM-tools to a greater extent early in a project is the way to go. One respondent summed up the other responses quite well by saying: *“I am of the opinion that there is a desire to use BIM. It's not completely painless yet, but we're well on our way. We must raise the quality of models at an earlier stage and make more demands on how a model for the tender stage should look and what it should contain. It is difficult to get these requirements through, since we as contractors are not involved early enough."*

Overall, the results of the survey have provided a clue to where the problems lie and how it is perceived by individuals. Some of the answers may seem obvious, but when carrying out the survey, many of the hypotheses have been confirmed independently and can be used to further discuss and find solutions to problems related to BIM and calculation/pre-project. “*Quick overview of what is to be built. If it is a good model, some quantities can easily be extracted for a quick calculation.”*

5. Discussion

When it comes to the survey directly linked to this paper, the feedback has been a good mix. A regular occurrence is that models early in the calculation phase are not complete enough to have an accurate price estimate of a building. Among other things, it is mentioned that the architect and designer have a limited preliminary project which is difficult to calculate accurately with the correct quantities. It can be anything from forgotten elements such as windows or walls to information in the various elements that is not included. can be forgotten. unclear and simply unfinished. Missing information about objects

Another aspect is competence. Although Norway is far ahead, there have been responses in the survey that indicate that there may be some lack of competence, as those who use BIM and calculation tools have more software and methods to stick to. The investigation has revealed that courses/training are in short supply. This can be explained by the fact that there is a greater proportion of older people (55-66 years) in construction who work full-time, compared to other industries. The report to which reference is made covers everyone in construction, including migrant workers and those who work outside on a construction site with a journeyman's certificate [10].

Some of the answers from the respondents is making a proof of this.

“Too much trust in models often leads to tunnel vision. It must be used correctly, and one must have the experience to see the details that do not appear in the model.”

“Want more use of dynamic calculation. That we get to the point where calculation is more of a natural part of the preliminary, sketch, detail and execution project phase. More of a natural part of the planning in these phases (and operations administration in the latter)”.

“*If you raise IT competence, influence the industry to have a standard template for BIM files and create calculation templates from this in ISY Byggoffice, you can quickly save a lot of time on automatic quantity withdrawal in ISY Byggoffice Office.”*

It is also important to mention the benefits of having a representative or official from competing contractors involved early on, to give them the opportunity to collaborate with the architect and create a compatible BIM file with the contractors' wishes and specifications included.

6. Conclusion

This paper aims to give an answer to the research question: *What are the advantages and disadvantages of using BIM in the estimation phase, and what measures can make this more efficient and user friendly.* The answer is that some measures must be initiated to make cost estimation more efficient in interaction with BIM tools: It is proposed to raise skills, implement requirements for models, implementation of dynamic calculation, involve calculation earlier in a project and involve the public sector to propose measures. The results show that there is a lack of competence and training for those who do not directly work with the development of models, for example people who use models for cost estimation. It has been identified that models have major shortcomings in such an early phase of a project. Secondly It has been identified that BIM-models used to calculations is not detailed enough. Integration of cost estimation earlier in the project development would have more influence on choices and solutions. The conclusion is that cost estimation has to be more efficient in the interaction with BIM, which includes implementation of stricter requirements for BIM-models used for dynamic calculations, skills has to be raised, and calculations should be involved earlier in the projects, and the public sector should be involved more to propose measures. It is also proposed that calculus becomes a dynamic subject that follows from the early phase to the final phase of a project, and integration of cost estimation earlier in the project development to have influence on choices and solutions.

7. References

[1] A. Brekkhus, "BIM-landet Norge," Byggeindustrien - Bygg.no, 2019, https://www.bygg.no/bim-landet-norge/1412487!/ (Acces date: 04.15.2023)

[2] BuildingSMART, Australasia, National Building Information Modelling Initiative, 2012.

[3] C. Merschbrock, and C. Nordahl-Rolfsen, "BIM Technology Acceptance Among Reinforcement Workers - The Case of Oslo Airport's Terminal 2," Electronic Journal of Information Technology in Construction, 21, pp 1-12, 2016, https://www.itcon.org/2016/1 (Acces date: 04.15.2023)

[4] Standard Norge. (2022). "BIM-objekter - Navngivning, typekoding og egenskaper for BIM-objekter og objektbiblioteker for byggverk,"Standard Norge.

[5] Katy Bartlett, J. L. (2020, pp.10-30). «Rise of the platform era: The next chapter in construction technology.", pp. 10-30, 2020, McKinsey & Company: https://www.mckinsey.com/industries/private-equity-and-principal-investors/our-insights/rise-of-th platform-era-the-next-chapter-in-construction-technology. (Acces date: 04.15.2023)

[6] https://www.symetri.no/produkter/solibri/ (Acces date: 04.15.2023)

[7] Naviate, "Naviate Simplebim", https://www.naviate.com/naviate-cloud/naviate-simplebim?__hstc=237267551.3b83642692eb648f0e1652c982eb2ee8.1659947844586.1659947844586.1660124309562.2&__hssc=237267551.1.1660124309562&__hsfp=1641316063&_gl=1*cd9nh8*_ga*NjU1NzQ2ODEzLjE2NTk5NDc4NDQ.*_ga_H94 (Acces date: 04.15.2023)

[8] S. Solem, " Prosjektstyring: ISY Byggoffice: Webområde for Norconsult informasjonssystemer," ,2022, https://www.nois.no/produkter/prosjektstyring/isy-byggoffice/ (Acces date: 04.15.2023)

[9] Neptuneproperties, https://neptuneproperties.no/vare-boliger/setra-vei/prospekt/arkitekturen (Acces date: 05.20.2023)

[10] H. K. L. Johannessen, "Tilstandsanalyse i bygg og anlegg," Trondheim: Direktoratet for arbeidstilsynet, 2013.

CONFIGURATION OF OBJECT DIVISION FUNCTION TO IMPROVE THE USABILITY OF THE DESIGN 3D MODEL IN THE CONSTRUCTION STAGE

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Abstract
The 3D model generated in the design stage is instrumental in preventing interferences and design errors during the construction process. However, it often does not consider the construction stage's activity concept, necessitating the remodeling of the 3D model for construction use. This reduces the reusability of the original 3D model, making it challenging to utilize it effectively during the construction stage. To address this issue, the authors propose a convenient function to divide the 3D model into construction activity units while retaining the attribute information. Although commercial CAD software like Dynamo has a 3D model division function, its use is complicated and requires additional software besides the 4D system for 4D simulation in the construction stage. The authors introduce a methodology and module that utilize the bounding box concept to simplify the division process after importing the 3D model into the 4D system. This eliminates the need for separate CAD software and allows for direct division into activity units within the 4D system and simultaneous simulation. The new division function is expected to improve the utilization of 3D models during the construction stage.

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Keywords: building information modeling, construction stage, activity, 3D model division, 4D system.

1. Introduction

1.1. Study background and objectives

Building Information Modeling (BIM) is a valuable tool for managing construction processes throughout their life cycle. During the design stage, a 3D model of the structure is created, and various attribute information, such as activities and cost, is added to the model. By utilizing such 3D models, potential issues that may arise during construction can be identified in advance by checking for interference between design components and errors in the design. Moreover, the 3D model generated during the design stage can provide a visual representation of the construction schedule and progress management through 4D simulations linked with the construction activities' schedule. Typically, 3D models generated during the design stage are structured based on the design unit components because it is challenging to consider the construction stage's activities. In other words, the information level of the 3D model generated during the design stage and the information level required during the construction stage differ from each other, making it difficult to use the model generated during the design stage directly.

Therefore, in many cases, 3D models are reconstructed based on activity units during the construction stage to recycle the 3D models generated during the design stage for the construction stage. In particular, to perform 4D simulations during the construction stage, the 3D models from the design stage must be modified, and new 3D models required for each activity unit must be created, incurring additional time and expense. This study establishes a division methodology to recycle the 3D models generated during the design stage as activity units in the construction stage. A division module based on the suggested method is also developed within a 4D system.

1.2. Research trend

Research on object disassembly of 3D models has been conducted from various perspectives. [2] studied object classification and disassembly of point cloud data by utilizing PointNet algorithms. [3] generated polygon recognition and vertex data based on the U-Net algorithm to propose methods to classify and disassemble structures. Furthermore, [4] studied the influence of learning data during deep-learning-based object disassembly in point cloud data. Disassembly utilizing point cloud data requires data collection and post-processing steps, and application to the construction stage through object disassembly in the design stage can face limitations as the process is semantic. It includes recognizing and classifying objects rather than physically disassembling them. [5,6] researched the classification of structural components and surface model generation based on the voxelization algorithm. [7] conducted a methodology study on triangular mesh model slices through parallel planes. [8] created multiple slice shapes in IFC models based on IfcOpenShell and utilized them for structural space analysis. [9] calculated vertex data of the surface model and conducted object disassembly studies through the objectification of the disassembly model after disassembly. Although vertex data utilization is common to the methods of this study, the division utilizes the triangular net vertex data of the surface model.

Previous studies on disassembly processes have primarily focused on semantic disassembly, which involves recognizing and labeling structures by applying deep learning models to point cloud data. A few studies have explored direct disassembly methods that physically disassemble 3D models, resulting in changes to attributes such as shape and volume. However, such studies may require specialized equipment and substantial amounts of training data to collect point clouds. Additionally, most studies have been limited to specific structures, such as buildings, and further research is needed to investigate direct disassembly of 3D models during the design and construction stages. In this study, authors present a simple disassembly method that utilizes Dynamo and a division module in a 4D system.

2. Design 3D model disassembly method

2.1. Generating a disassembly partition of the 3D model

Object segmentation is an important process in 3D modeling that involves dividing a 3D object into smaller parts or segments. In the context of construction, object segmentation is often used to divide a design model into smaller activity units that can be more easily managed and simulated during the construction stage. Dynamo, which is a visual programming language built for Revit, can be used to create nodes for object segmentation, including cutting functions that designate the disassembly direction and shape of the 3D model. These nodes can be used to segment the 3D model into activity units, which can then be further optimized for use in the construction stage. By using Dynamo to segment the 3D model in this way, it becomes easier to determine a specific construction order, match detailed construction activity units, and disassemble the model for use in the construction stage. This process can significantly improve the reusability of the original 3D model created during the design stage, and help to streamline the overall construction process.

After the user selects the model to be disassembled, the function that allows the user to configure the disassembly partition freely is shown as a Dynamo script in Fig. 1. The model object is disassembled according to a previously generated disassembly partition. The user can freely configure the disassembly partition of the structure by designating the length and direction of the vertical and horizontal structures. The disassembly specifics can be subsequently input for the disassembled 3D model to be utilized in the construction and maintenance stages.

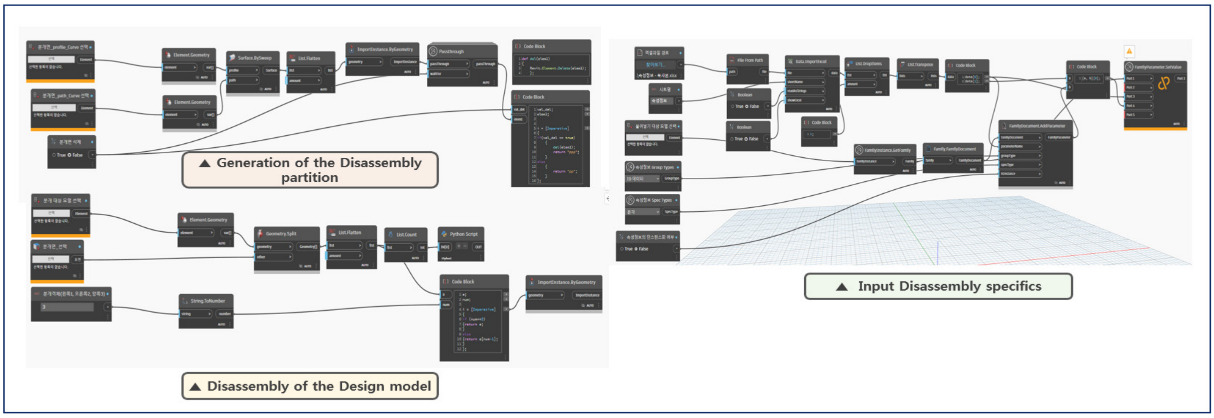


Fig. 1. Dynamo script configuration for disassembling the 3D model

2.2. Configuring the disassembly process with Dynamo

The attributive information of the initial design model must be maintained in the disassembly process of the 3D model generated in the design stage. Any additional attributive information must be input according to how the disassembling proceeds. However, the design models consist of hundreds or thousands of objects, indicating that it is inefficient for users to directly select models that need to be disassembled in the design model. Thus, the model to be disassembled, and the number of components to divide a design model using Dynamo need to be fixed. Since several iterations may be necessary, a Dynamo script capable of handling such actions is configured to disassemble the design model.

2.3. Generating bounding box to design 3D models

The upper portions of Fig. 2 show the script configuration that enables objects to be disassembled by the bounding box after setting the model to be disassembled and a number of components in Revit Dynamo. Geometrical information is extracted from the bounding box of each object to be disassembled in the x-, y-, and z-directions, as shown in detail in the lower portion of Fig. 2.

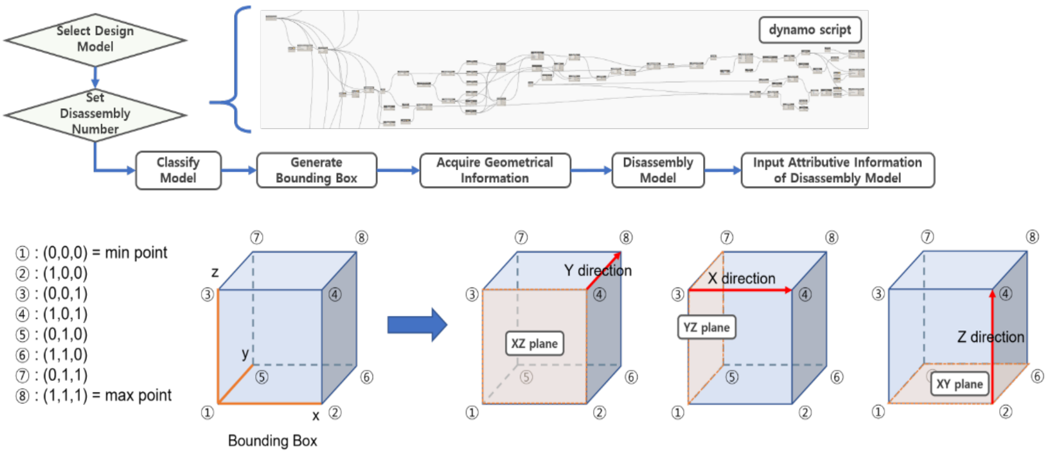


Fig. 2. Bounding box configuration of the 3D model using Dynamo

3. Disassembly of 3D model of bridges

3.1. Configuration of the disassembly information of the 3D model

The user first defines the number of components and parts of objects for disassembly. Then, the design model is disassembled using the configured Dynamo script (Fig. 3). For example, an abutment created as a single object in the design stage must be executed three times vertically in the construction stage.

The user sets the abutment to "3" in the Dynamo script, inputting the number of components to obtain an object disassembled into three components in the z-direction (as shown on the right side of Fig. 3).

To use the disassembly model object in detail, a new method is required to easily determine: 1) the number of divisions for a given component of the disassembly model objects, and 2) the order of disassembly model objects. Therefore, a procedure is established for inputting information about the model before disassembly and the number of components to be conducted as attributes. This allows user to check the details of disassembly, as shown on the right side of Fig. 3. The specifics of disassembly can be configured by combining the object name already input in the existing design model and disassembly information in the WBS Code, also shown on the right side of Fig. 3. Thus, regardless of which disassembly model object is selected, the attributive information before and after disassembly can be identified simultaneously, enhancing the utilization and convenience of the disassembly model.

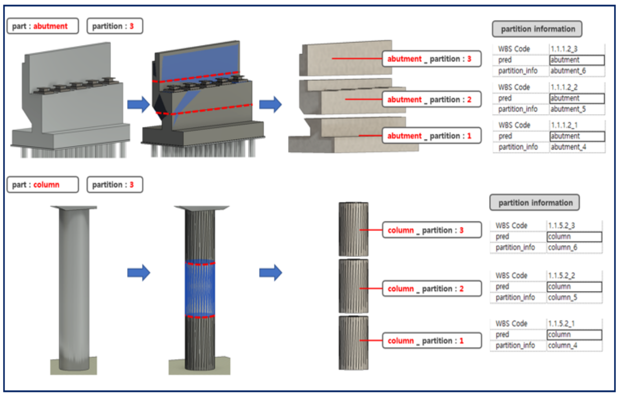


Fig. 3. Input details of the 3D model disassembly

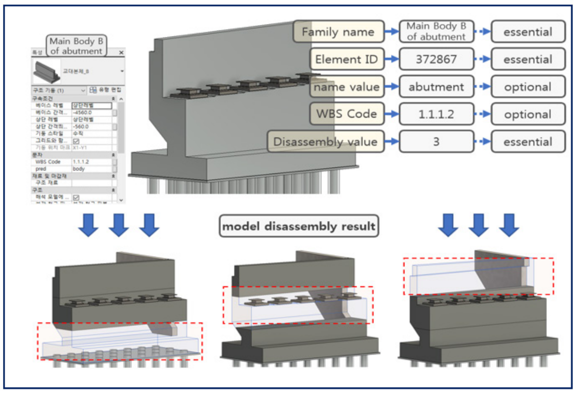


Fig. 4. Configuring the schedule of disassembled 3D models

3.2. Configuring the schedule of 3D models

The schedule information of the disassembly model is generated by utilizing the disassembly information input after the design 3D model has been disassembled. The abutment model of the bridge receives a disassemble value (3) from the user, as shown in Fig. 4. Accordingly, an abutment model constituting one object is divided into three segments, as shown in the lower left portion of Fig. 4. Each segment receives a “name value_disassemble value” of abutment_1, abutment_2, and abutment_3. In other words, the schedule information is readily generated by utilizing the essential information included in the 3D design model. In addition, the Dynamo script is prepared so that the value selectively input by the user, such as the WBS Code, receives a “WBS Code_ disassemble value”.

After extracting information such as abutment_1, abutment_2, and abutment_3 allocated to the disassembly model and reallocated WBS Code, the schedule information regarding the construction details of the relevant model is generated. A specific schedule is established in this process by designating the abutment construction order of ‘rebar installation’, ‘formwork installation’, ‘concreting’, ‘formwork remove’, and ‘other’ in advance and enabling repetition of the above activities.

Thus, when users are configuring the schedules of abutments that form the design 3D model, they establish a detailed schedule divided by execution, as shown in the ‘Partition and Recycle model’ column in Table 1. The ‘Existing 3D model’ column in Table 1 exhibits a schedule comprised of only five processes.

Table 1: Organization system of activity units of 3D models before and after disassembly

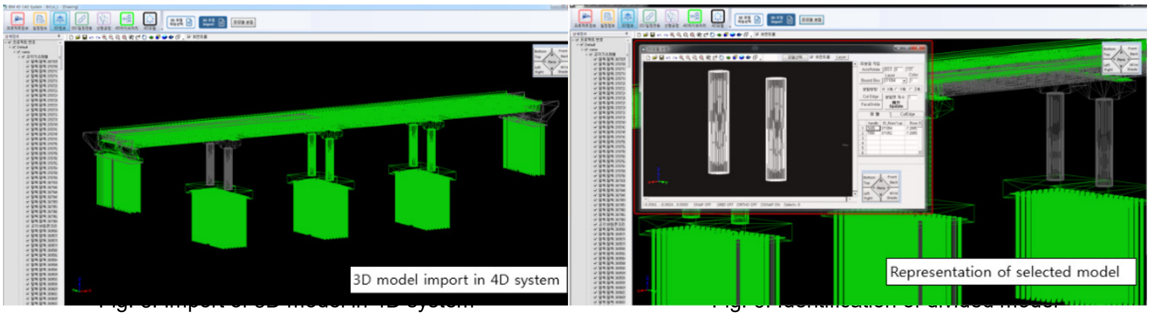
Existing 3D model	Disassembly and Recycle model
▼ **Abutment**	▼ **Abutment**
Rebar installation	▼ **Abutment_1**

Formwork installation	Rebar installation
Concreting	Formwork installation
Formwork remove	Concreting
Etc.	Formwork remove
	Etc.
	▼ **Abutment_2**
	Sub-process X5
	▼ **Abutment_3**
	Sub-process X5

4. Division module of 3D model in 4D system

4.1. Import of divided model and selection of divided object

To divide a 3D object in a 4D system, first select a design model from the ‘3D Information’ menu and then import it into the 4D system as shown in Fig. 5. Once the design model is selected and imported into the 4D system from the ‘3D Information’ menu, the ‘3D model division’ function can be activated. Clicking on the ‘Split 3D model’ button will open a 3D model split window, where detailed information of the model to be divided can be checked. Users can select the specific object or multiple objects they want to divide by dragging. After the selection is made, clicking the mouse will bring up the division function viewer, as shown in Fig. 6.



4.2. Generation of bounding box and division plane

Fig. 7 shows the detailed division screen after selecting the model to be divided. If the user selects the ‘Bounding box’ button in the activated division window, the user can generate a bounding box of the model object and can check the information on the two pier column objects that the user selected for division. In addition, if the model to be divided is multiple objects, objects can be individually selected from the layer. A bounding box can be created for each model, allowing different divisions between multiple objects. When a bounding box is created, a guideline is displayed as shown in Fig. 8 so that the generated bounding box can be checked in detail. The user can use the 3D model division function more conveniently by providing the user with a guideline for the direction and generation of the division surface.

After selecting the detailed object to be divided and creating the bounding box, the user can input the number of divisions. After entering the number of divisions, if the 'Cut edge' button is selected, the user can check that the guideline is marked. The corresponding guideline becomes the division direction, and the detailed coordinates are located in the middle of the division function window. Accordingly, the user can check the specific coordinates of the guideline, and freely configure the division direction and surface by freely moving the guideline. Divided parts can be intuitively grasped through division lines and colors.

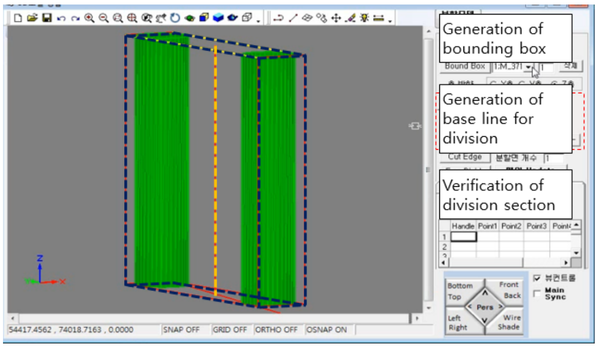


Fig. 7. Generation of bounding box of division model

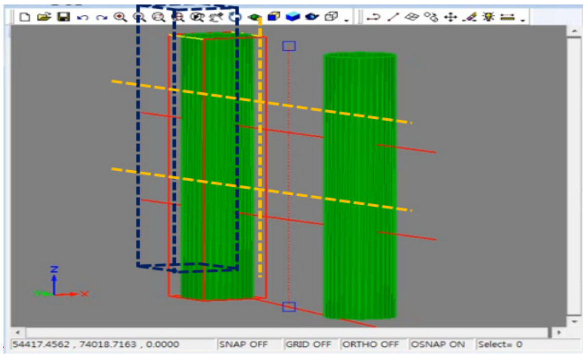


Fig. 8. Divided model using division module un 4D system

5. Conclusions

With the increasing use of building information modeling (BIM) in the construction industry, the 3D models developed during the design stage are becoming more important for the construction stage as well. This study presents a method to disassemble a 3D model for recycling the construction activity units and verifies the utility of division module within the 4D system using the segmented model. By using the Dynamo script to disassemble the model in the desired direction, number, and level, the construction stage 3D models can be efficiently recycled for the 4D simulation. Additionally, the division module constructed within the 4D system allows for the 3D model to be divided into detailed activity units without the need for external software, improving the convenience of the 4D system. This method contributes to the utilization and efficiency of BIM functions in the construction stage, promoting better collaboration and communication between designers and contractors.

Acknowledgements

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References

[1] Ciribini, A.L.C., Mastrolembo Ventura, S. and Paneroni, M. “Implementation of an interoperable process to optimize design and construction phases of a residential building,” A BIM Pilot Project. Automation in Construction, 71(1), pp. 62-73, 2016, doi: 10.1016/j.autcon.2016.03.005

[2] Qi, C.R., Su, H., Mo, K. and Guibas, L.J, “PointNet: Deep learning on point sets for 3D classification and segmentation,” Proceedings of the IEEE Conference on Computer Vision and Pattern Recognition (CVPR),” pp. 652-660, 2017, doi: 10.3390/s22093209

[3] Li, W., Zhao, W., Zhong, H., He,C. and Lin, D., “Joint Semantic-geometric Learning for Polygonal Building Segmentation,” Proceedings of the AAAI Conference on Artificial Intelligence, pp. 1958-1965, 2021, doi: 10.1609/aaai.v35i3.16291

[4] Ryu, Y.M., Kim, B.K. and Park, J.J, “Effect of learning data on the semantic segmentation of railroad tunnel using deep learning,” Journal of the Korean Geotechnical Society, 37(11), pp. 107-118, 2021, doi: 10.1016/j.autcon.2021.104425

[5] Pan, Y., Dong, Y., Wang, D., Chen, A. and Ye, Z, “Three-dimensional reconstruction of structural surface model of heritage bridges using UAV-based photogrammetric point clouds,” Remote Sensing, 11(10), 2019, doi: 10.3390/rs11101204

[6] Xu, Y., Tong, X. and Stilla U, “Voxel-based representation of 3D point clouds: methods, applications, and its potential use in the construction industry,” Automation in Construction, 126, 2021, doi: 10.1016/j.autcon.2021.103675

[7] Minetto, R., Volpato, N., Jorge, S., Gregori, R. and Murilo, V.G.S, “An optimal algorithm for 3D triangle mesh slicing,” Computer-Aided Design, 92, pp. 1-10, 2017, doi: 10.1016/j.cad.2017.07.001

[8] Atmodiwirjo, P., Johanes, M. and Yatmo, Y.A. “Development of multi-slice analytical tool to support BIM based design process,” IOP Conference Series: Materials Science and Engineering, 185(1), pp. 1-6, 2017, doi: 10.1088/1757 899X/185/1/012009

[9] Lee, S.S., Lee, M.J., Jeong, J.Y. and Seo, J.W, “Design of flexible BIM system for alignment-based facility,” KSCE Journal of the Korean Society of Civil Engineers, 34(2), pp. 677-685, 2014 doi: 10.12652/Ksce.2014.34.2.0677

IMPACT OF FLUIDIZED BED FLY ASH ON STRENGTH DEVELOPMENT OF SELF-COMPACTING CONCRETE

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Abstract

The use of self-compacting concrete (SCC) instead of traditional vibrated concrete has many advantages, which are most evident through the increased efficiency of SCC concrete under the influence of the environment. However, its use requires careful planning of concrete works and careful optimization of concrete mix design. SCC usually includes large amount of fine particles which ensure cohesiveness of the mixture and provide enough excess paste which is necessary for achieving adequate flow properties. When pulverized coal fly ash is used as a fine mineral additive, its spherical particles reduce water demand, and slow pozzolanic reactions reduce permeability and this leads to increased durability. Nowadays, pulverized coal combustion technology is being replaced by combustion in a circulating fluidized bed, which is characterized by lower energy consumption. Circulating fluidized bed fly ash particles are irregularly shaped and differ in chemical composition from pulverized coal fly ash. In this paper the possibility of designing SCC with the addition of circulating fluidized bed fly ash is being investigated. SCC mixes with different amounts of fly ash were designed and its properties in the fresh state were tested using slump-flow, J-ring and L-box measurements. Compressive strength was tested in the period from 2 days to 90 days to evaluate the effect of circulating fluidized bed fly ash on strength development.

Keywords: fly ash, limestone quarry dust, supplementary cementitious materials, self-compacting concrete

1. Introduction

Pulverized coal fly ash has gained considerable importance as a supplementary cementitious material due to its pozzolanic properties, but also due to the improved workability of concrete attributed to the spherical shape and plain surface of ash particles. Nowadays, circulating fluidized bed combustion technology is being more widely accepted as a method for production of heat and electrical energy because it is more energy efficient. In conventional pulverized coal-fired boilers, combustion takes place at temperatures between 1150 °C and 1750 °C which results in the melting of the majority of the minerals contained in the coal which is crucial for the formation of spherical particles [1]. In fluidized bed combustion the temperature of combustion is below the melting point (up to 900 °C). Because of lower temperature of combustion and interaction of coal with bed material, fluidized bed fly ash is more crystalline and irregularly shaped [2].

Utilization of fluidized bed fly ash in building materials has been widely investigated during the last decade [3,4]. It was shown that these ashes compared to pulverized coal fly ash poses self-cementitious properties [3,4,5]. Increasing the content of fluidized bed fly ash usually increases the water demand of the mix [6,7]. When used as a cement replacement, especially at higher replacement ratios it decreases strength but at lower dosages strength could also increase which is attributed to the denser microstructure [3,4,7]. The filling effects are also used to explain reduced permeability and improved durability of concrete made with fluidized bed fly ash [8,9,10].

The application of fluidized bed fly ash is currently outside the scope of the standard for fly ash for concrete (EN 450-1:2012). It may be used as a supplementary cementitious material however, its performance as concrete pozzolan is not yet well established [1], probably due to its high variation in chemical composition depending on the source of fuel [3]. In this work possibility of producing SCC with circulating fluidized bed fly ash is being investigated. Mixes with different amount of fly ash used as a cement replacement and/or filler were tested using standardized methods for SCC. Besides fresh concrete properties impact of fly ash on compressive strength development has been evaluated.

2. Materials and methods

2.1. Characterization of component materials

Cement used was Portland cement type CEM I 52,5 N (CEM I) according to classification in European standard EN 197-1:2011. Limestone quarry dust (LQD) originated from the same quarry as the aggregate used in this work. LQD is a by-product generated during mining and crushing processes of aggregate production. The problem of generation of excess amounts of LQD is often present at aggregate crushing facilities. It is usually possible to influence the amount of LQD generated by optimization of crushing technology [11]. LQD requires adequate handling and storage in order to reduce the pollution of the surrounding areas by small airborne particles. LQD had more than 85 % of particles passing the 0,063 mm sieve (Fig. 1.) as determined by air jet sieving method (EN 933-10:2009) and in this work it was used as filler for design of SCC. Fly ash (FA) originated from thermal power plant Stanari located in the central part of Bosnia and Hercegovina. Power plant uses lignite coal as a fuel which is incinerated at ≈ 850 °C using circulating fluidized bed combustion technology. Chemical and physical properties of this FA have already been presented in [12]. Pozzolanic oxide content (SiO_2+Al_2O_3+Fe_2O_3) of FA is 78,85 % [12] which indicates its potential to serve as a cement replacement material. It also has finer particles than cement with median particle size of 18,8 μm (Table 1). The particle size distribution (PSD) of powder materials (CEM I, LQD and FA) is shown in Fig. 1. The PSD of CEM I and FA was analysed by a laser diffraction method using a dry measurement (Shimadzu SALD 3101 Instrument) while the PSD of LQD was analysed by air-jet sieving method. Density of powder materials was determined according to standard ASTM C188-17 (Table 1).

Water demand of powder represents the minimum amount of water necessary to mix with powder to form a cohesive paste. At this state bonds between solid particles are strongest and maximum packing density is achieved [13,14]. Water demand and packing density are both simple to measure and can be used to qualitatively estimate effects of adding mineral admixtures on density and workability of the concrete. Different methods have been proposed for evaluation of water demand of powders [15]. In this work minimum water requirement was determined by combined use of standard consistency test (EN 196-3), mini-slump test [16] and visual observation. It was determined that the water requirement of FA is approximately three times of that of CEM I or LQD (Table 1). Packing density of each powder was determined by measuring mass of the sample compacted in the cylinder mould with a volume of 70 cm^3 and then volume of solid particles is calculated from known data about water/powder ratio and densities of water and powder. It was determined that LQD had the highest packing density and the lowest packing density was measured for FA (Table 1).

Aggregate used was crushed limestone. Three size fractions 0/4 mm, 4/8 mm and 8/16 mm were used for making concrete. Particle size distribution of aggregate is presented in Fig.1. Water absorption was 0,6 %, 0,4 % and 0,3 % for fractions 0/4 mm, 4/8 mm and 8/16 mm respectively. The average density of aggregate was 2,68 kg/dm^3. Superplasticizer used was MasterEase 7007 from Master Builders.

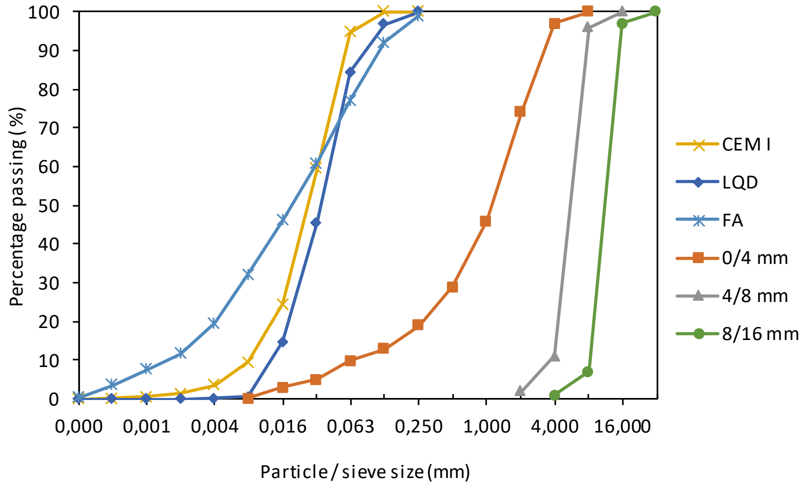

Fig. 1. Particle size distributions of powders and aggregates

Table 1. Physical properties of cement, limestone quarry dust and fly ash

Property	CEM I 52,5 N	Limestone quarry dust	Fly ash
Median, d_{50} (μm)	26,5	33,7	18,8
Density (g/cm^3)	3,01	2,72	2,39
Water requirement (-)	0,28	0,22	0,75
Wet packing density (-)	0,577	0,647	0,385

2.2. Concrete mix design and testing methods

One of the goals of this work was to design mixes that will have reduced cement content by replacing it with FA while meeting the requirements for SCC. Another goal was to maximize the use of both LQD and FA since considerable quantities of both materials are currently being landfilled. Concrete mix compositions are given in Table 2. Mixes M1-M8 are designed with the same powder content (CEM I+LQD+FA) of 580 kg per 1 m^3. Both CEM I and FA were treated as binder and mixes were designed with water/binder (w/b) ratio of 0,4, 0,45 and 0,5. Mix M1 has been selected as reference and was made without FA. In mixes M2 and M3 CEM I have been partially replaced with LQD. Mixes M4 and M5 were made with w/b ratio of 0,4. In mix M4 50 % of LQD was replaced with FA while in mix M5 cement was also partially replaced with FA. Mixes M6-M8 were made with w/b ratio 0,45 and different amounts of CEM I replaced by FA. Mix M9 has been designed with powder content of 315 kg per 1 m^3 with an aim to maximally reduce cement content while maintaining SCC properties. To avoid segregation in mix M9 aggregate particle size distribution has been modified compared to mixes M1-M8 by increasing the percentage of 0/4 mm aggregate fraction. Quantity of superplasticizer in mixes was adjusted to achieve adequate flowability required for SCC.

The mixing of the concrete was performed in a compulsory mixer with a capacity of 75 litres. Before mixing, all constituents were conditioned in a laboratory for approximately 1 day to equilibrate temperature differences between constituents. The mixing procedure similar to that described in [17] was followed. Fine and coarse aggregates were first homogenized in a mixer and shortly after about one third of the mixing water was added and mixed for 30 seconds. Then cement and mineral additive were added and mixed for another 30 seconds and the second third of water was added and mixed for one minute. The superplasticizer dissolved in remaining water was introduced into mixer and mixed for another two minutes and then left for a two-minute rest. Concrete was then mixed for additional two minutes to complete the mixing sequence.

In the fresh state temperature and density of concrete were measured. Density was measured using pressure method on a sample with volume of 8 litres. Standardized tests for self-compacting concrete were used to evaluate flowability, viscosity, passing ability and segregation resistance. Flowability was evaluated by slump-flow test according to standard EN 12350-8:2019, viscosity was evaluated by measuring t_{500} time in slump-flow test and by V-funnel test described in EN 12350-9:2010. Passing ability was evaluated by L-box test with 3 bars (EN 12350-10:2010) and by J-ring with 12 bars (EN 12350-12:2010). Segregation resistance was evaluated by sieve segregation test (EN 12350-11:2010).

Table 2. Concrete mix composition (quantities per 1 m^3 of concrete).

Mix Designation	M1	M2	M3	M4	M5	M6	M7	M8	M9
CEM I (kg)	400	355	320	400	350	400	350	300	234
Water (kg)	160	160	160	196	196	221	221	221	200
Superplasticizer (kg)	8,5	10,3	11,0	12,0	13,8	10,2	9,8	9,8	4,7
LQD (kg)	180	225	260	90	90	90	90	90	-
FA (kg)	-	-	-	90	140	90	140	190	81
CEM I+LQD+FA (kg)	580	580	580	580	580	580	580	580	315
Water/cement ratio	0,40	0,45	0,50	0,49	0,56	0,55	0,63	0,74	0,85
Water/binder ratio	0,40	0,45	0,50	0,40	0,40	0,45	0,45	0,45	0,63
Water/powder ratio	0,28	0,28	0,28	0,34	0,34	0,38	0,38	0,38	0,63
Aggregate 0-4 mm (kg)	941	941	941	877	872	843	838	833	1248
Aggregate 4-8 mm (kg)	342	342	342	319	317	307	305	303	249
Aggregate 8-16 mm (kg)	428	428	428	399	397	383	381	378	341

The concrete compressive strength was tested on concrete cubes with a side length of 150 mm at 2, 7, 28 and 90 days of age according to standardized procedure (EN 12390-3:2019). All specimens were cast without compaction and vibration. After casting, the specimens were kept covered in the laboratory for 24 h until demoulding to reduce water evaporation. Then, the specimens were placed in a water bath at temperature of 20 ± 2 °C.

3. Results and discussion

3.1. Fresh concrete properties

Results of fresh concrete properties are presented in Table 3. Temperature of fresh concrete varied between 23,5 °C and 28,7 °C. These variations are partly caused by initial temperature differences in the constituents between mixes due to variation of air temperature in the laboratory. It can also be seen that mixes M6-M8 made with highest water content had lowest initial temperature which indicates that these temperature variations are also caused by increased heat capacity of these mixes. Increased water content in mixes M4-M8 is also the main reason for reduced fresh concrete density.

Replacing CEM I with LQD led to increased water demand. As presented in Table 1 LQD has lower water demand and higher packing density than CEM I. Therefore, increased water demand could be explained by increased packing density of concrete which also led to increased cohesiveness of the mix. This is supported by increased density and compressive strength of mix M2. The same effect is not apparent in mix M3 because there is 80 kg/m^3 less binder compared to mix M1 and density of LQD is lower than that of cement (Table 1). Segregation resistance measurement shows that replacing CEM I with LQD increased likelihood of segregation (class SR1, see Table 4).

In mixes containing FA it was impossible to achieve adequate flowability of concrete without increasing water content. This is the reason why mixes M4 and M5 were designed with increased amount of water compared to reference mix. Both mixes had increased passing ability as determined by J-ring and L-box test and had good segregation resistance (Table 3 and Table 4). Increasing the amount of FA required further increase in the dosage of the superplasticizer. During trials there was also an attempt to produce mix with 190 kg/m³ of FA and 196 kg/m³ of water but it was impossible to achieve required workability regardless of the dosage of the superplasticizer.

Further increase of water content in mixes M6-M8 enabled reduction of the superplasticizer dosage while maintaining good segregation resistance and passing ability. All mixes made with powder content of 580 kg/m³ containing FA had very good passing ability according to J-Ring test results (Table 3 and Table 4).

Mix M9 could be classified as eco-concrete because it was made with very low cement and powder content [16,18]. Mix M9 had low viscosity and good segregation resistance while its passing ability was lower compared to mixes with high powder content containing FA (Table 3, Table 4).

Table 3: Properties of fresh concrete

Mix Designation	M1	M2	M3	M4	M5	M6	M7	M8	M9
Temperature (°C)	27,2	28,7	27,0	26,0	25,5	23,5	24,8	25,0	28,0
Fresh density (kg/m³)	2420	2430	2410	2350	2365	2343	2310	2310	2360
Slump flow, SF (mm)	690	620	680	700	700	740	630	650	720
SF t_{500} (s)	2,5	2,0	2,3	2,0	3,5	1,0	2,4	2,3	1,1
V-funnel (s)	13,5	13,0	11,5	10,5	15,5	5,0	10,0	13,0	4,7
J-ring - 12 PJ (mm)	17	12	9	9	9	3	6	8	14
J-ring SF (mm)	690	680	700	760	760	770	640	660	690
L-box PL2 (-)	0,84	0,82	0,88	0,94	0,93	1,00	0,86	0,89	0,83
GTM SR (%)	7	19	19	12	12	13	6	7	5

Table 4: Categorization of SCC according to EN 206:2021:2013+A2:2021

Mix Designation	M1	M2	M3	M4	M5	M6	M7	M8	M9
Flowability - Slump flow, SF (mm)	SF2	SF1	SF2	SF2	SF2	SF2	SF1	SF1	SF2
Viscosity -SF t_{500} (s)	VS2	VS1	VS2	VS1	VS2	VS1	VS2	VS2	VS1
Viscosity - V-funnel (s)	VF2	VF2	VF2	VF2	VF2	VF1	VF2	VF2	VF1
Passing ability - J-ring - 12 PJ (mm)	×	×	PJ1	PJ1	PJ1	PJ1	PJ1	PJ1	×
Passing ability L-box PL2 (-)	PA2	PA2	PA2	PA2	PA2	PA2	PA2	PA2	PA2
Segregation resistance - GTM SR (%)	SR2	SR1	SR1	SR2	SR2	SR2	SR2	SR2	SR2

3.2. Compressive strength

Compressive strength test results are presented in Fig. 2. Compressive strength results in Fig. 2 represent average strength obtained on three specimens. Based on the 28-day strength mixes M1, M2, M4 and M5 could be classified as high strength concrete according to the European standard EN 206:2021. Mixes M1, M4 and M5 are made with w/b ratio of 0,4 and mix M2 had w/b ratio 0,45. Mix M2 also has the highest 90-day compressive strength of 90,7 MPa. As already mentioned, this supports the conclusion that, although cement content is reduced improved packing density led to the higher compressive strength of mix M2. Mixes M3, M6, M7 and M8 fulfil requirements for concrete strength class C50/60 and mix M9 can be classified as C30/37 strength class according to EN 206:2021.

Estimation of the potential reactivity of FA is usually based on its chemical composition. The contribution of pozzolanic reactions to strength becomes significant after 7 or 28 days of hydration [19]. All mixes with FA (M4-M9) had strength increase in the period from 28-90 days approximately equal to mixes made without FA. However, compressive strength of mixes M6-M8 shows that reduction of the cement content of 100 kg/m^3 and replacing it with FA had a very little effect on compressive strength. In fact, highest 90 day compressive was determined on samples from mix M8 which had the highest replacement of CEM I with FA. Replacing 50 kg/m^3 of CEM I with FA in mix M5 compared to mix M4 resulted in slower initial strength development but in the period between 7-28 days faster strength development was measured in mix M5. This shows that FA had significant contribution to compressive strength of concrete which could be attributed to the pozzolanic activity of FA.

In Fig. 3 linear regression results are given for correlation of 28-day compressive strength with w/c and w/b ratio. Based on coefficients of determination R^2 there is a higher level of correlation between compressive strength and w/b ratio (R^2=0,89) then between compressive strength and w/c ratio (R^2=0,72). This also shows that FA had a large contribution to compressive strength of concrete mixes analysed in this research.

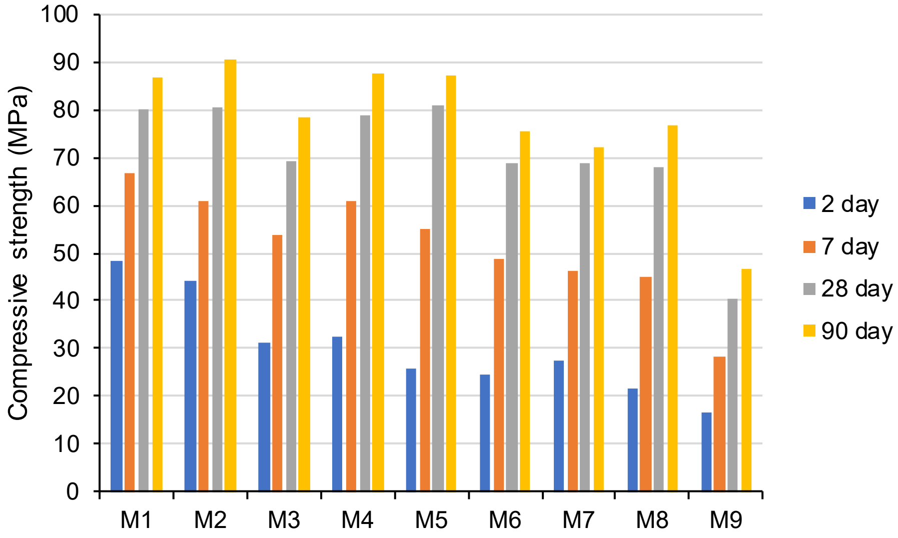

Fig. 2. Compressive strength development

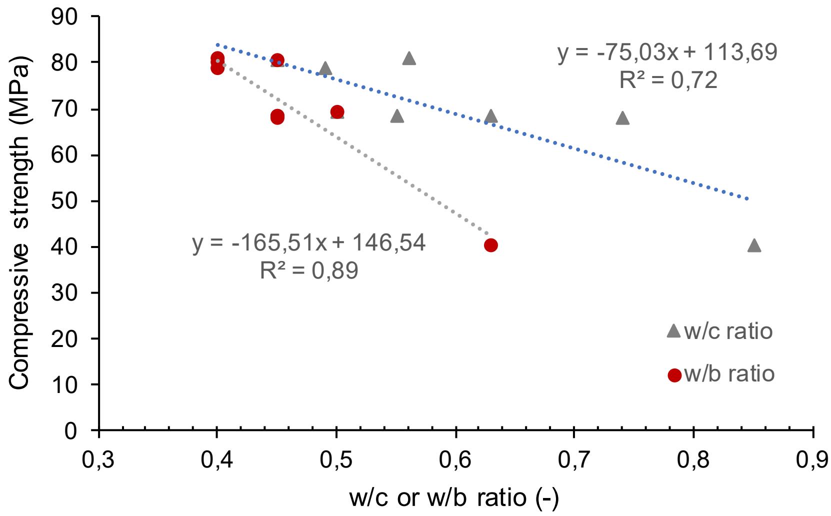

Fig. 3. Correlation of 28-day compressive strength with w/c ratio and w/b ratio

4. Conclusions

Addition of circulating fluidized bed fly ash in concrete as a cement replacement and a filler in SCC concrete resulted in increased water demand. Characterisation of powder materials showed that the water requirement of FA is approximately three times of that of CEM I or LQD. Increased water demand can be attributed to the irregular shape of FA particles and to the increased fineness compared to CEM I and LQD. Adjusting the water content and the amount of superplasticizer in the mix enabled production of SCC with adequate flowability. Incorporation of FA contributed to the increased passing ability of SCC as determined by J-ring test.
Replacing up to 100 kg/m^3 of CEM I with FA didn't reduce 28-day or 90-day compressive strength, although somewhat lower strengths were present at 2 and 7 days. This could be related to the slow pozzolanic reactions of FA.
SCC with very low amount of cement (234 kg/m^3) and the total powder content of 315 kg/m^3 was achieved with 28-day compressive strength of 40 MPa. For higher strength mixes with larger amount of powder further investigation should try to reduce the superplasticizer dosage necessary achieve targeted fresh and hardened concrete properties.

Acknowledgements

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References

[1] Rajabipour, F.; Zahedi, M.; Kaladharan, G. Evaluating the Performance and Feasibility of Using Recovered Fly Ash and Fluidized Bed Combustion (FBC) Fly Ash as Concrete Pozzolan; Final Project Report; The Pennsylvania State University: University Park, PA, USA, 2020.
[2] Li, X.-G.; Chen, Q.-B.; Huang, K.-Z.; Ma, B.-G.; Wu, B. Cementitious properties and hydration mechanism of circulating flu-idized bed combustion (CFBC) desulfurization ashes. Constr. Build. Mater. 2012, 36, 182–187, doi:10.1016/j.conbuildmat.2012.05.017.
[3] Ohenoja, K.; Pesonen, J.; Yilniemi, J.; Illikainen, M. Utilization of Fly Ashes from Fluidized Bed Combustion: A Review, Sustainability 2020, 12, 2988; doi:10.3390/su12072988
[4] Jia, G.; Wang, Y.; Yang, F. A Review on the Application of Circulating Fluidized Bed Fly Ash in Building Materials, Advances in Materials Science and Engineering, Volume 2022, 7099430, https://doi.org/10.1155/2022/7099430
[5] Li, X.; Chen, Q., Huang, K.; Ma, B.; Wu, B. Cementitious properties and hydration mechanism of circulating fluidized bed combustion (CFBC) desulfurization ashes, Construction and Building Materials 36 (2012), 182-187, http://dx.doi.org/10.1016/j.conbuildmat.2012.05.017
[6] Sheng, G.; Zhai, J.; Li, Q.; Li, F. Utilization of fly ash coming from a CFBC boiler co-firing coal and petroleum coke in Portland cement. Fuel 2007, 86, 2625–2631. https://doi.org/10.1016/j.fuel.2007.02.018
[7] Horszczaruk, E.; Seul, C. Use of Fluidized Bed Combustion Fly Ash as a Partial Substitute for Cement in Underwater Concrete Mixes, Materials 2022, 15, 4809. https://doi.org/10.3390/ma15144809
[8] Jozwiak-Niedzwiedzka, D. Estimation of chloride migration coefficient in air-entrained concretes containing fluidized bed combustion fly ash. Arch. Civ. Eng. 2012, 58, 25–38. doi: 10.2478/v.10169-012-0002-3
[9] Zahedi, M.; Jafari, K.; Rajabipour, F. Properties and durability of concrete containing fluidized bed combustion (FBC) fly ash, Construction and Building Materials 258 (2020) 119663, https://doi.org/10.1016/j.conbuildmat.2020.119663
[10] Lagosz, A.; Tracz, T.; Mroz, R. Extending the Life Cycle of Cement Binders by Partially Replacing Portland Cement with Different Types Fluidized Bed Combustion Fly Ash, Minerals 2021, 11, 690. https://doi.org/10.3390/min11070690
[11] Mitchell, C.J.; Mitchell, P.; Pascoe, R.D., Quarry fines minimisation: can we really have 10mm aggregate with no fines?, Proceedings of the 14th Extractive Industry Geology Conference. EIG Conferences, 2008. pp. 37-44
[12] Štefanec, P.; Kolman, D.; Radoš, A.; Pulić, Š.; Gabrijel, I., Variability of coal fly ash for use in the cement industry // Proceedings of the Creative Construction e-Conference (2022), pp. 256-261. https://doi.org/10.3311/CCC2022-033
[13] Powers, T.C. The properties of fresh concrete, John Wiley & Sons, 1968.
[14] De Larrard, F. Concrete Mixture Proportioning A Scientific Approach, CRC Press, 1999.
[15] Wong, H.H.C.; Kwan, A.K.H, Packing density of cementitious materials: part 1 – measurements using a wet packing method, Materials & Structures, (2008) 41:689-701. DOI 10.1617/s11527-007-9274-5
[16] Fennis, S.A.A.M, Design of Ecological Concrete by Particle Packing Optimization, Doctoral thesis, Delft University of Technology, Netherlands, 2011.
[17] Jelčić Rukavina, M.; Gabrijel, I.; Bjegović, D. Modifications of dolomite-based self-compacting concrete properties using mineral additives. Tehnički vjesnik, (2015) 22 (1), 233-240. https://doi.org/10.17559/TV-20140327212200
[18] Mueller, F.V., Wallevik, O.H., Khayat, K.H., Considerations for Designing Low-Powder Self-Compacting Concrete; Eco-SCC, International Symposium on Environmentally Friendly Concrete Eco-crete, Reykjavik, August, 2014, pp. 121-128.
[19] Lawrence, P.; Cyr, M.; Ringot, E. Mineral admixtures in mortars effect of type, amount and fineness of fine constituents on compressive strength. Cem. Concr. Res. 2005, 35, 1092–1105, doi:10.1016/j.cemconres.2004.07.004.

NOVEL DEVELOPMENTS TO PRECAST BRIDGE GIRDER TECHNOLOGY BY THE BME-ZÁÉV RESEARCH COOPERATION

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Abstract
The Competence Center on Safety Science and Technology joints significant research effort of the Budapest University of Technology and Economics (BME) and the potential industrial partners on several fields of industrial safety. On the building industry branch of this project novel bridge girder technologies have been developed by the cooperation of the Civil Engineering Faculty of BME and the ZÁÉV Construction Co Ltd. (ZÁÉV). These technologies aim to reduce the production time and cost, utilize the structural benefits of post-tensioning and ensure sufficient durability for products subjected to extreme chloride and freeze-thaw effects. The main outcome of the project is the full development of a brand-new, 0,9 m high bridge girder family made of self-compacting concrete. The use of self-compacting concrete is completely new in bridge girder technology in Hungary where high compressive strength both at young age and sufficient durability during 100 years of service life are the major demands to complete. For this purpose two mixes including limestone powder and CEM III type cement as additions were developed and tested in laboratory and factory conditions. The practical applicability of internal bonded and unbonded as well as external unbonded types of post-tensioning with various layouts were tested on two-span prototype systems. Following the international trends to extend service life or to further improve the durability of bridges subjected to extreme environmental conditions, possible solutions can be either to use embedded fibre reinforced polymer (FRP) bars instead of traditional steel ones as reinforcement in concrete or to structurally combine them with post-tensioning of full corrosion protection in hybrid-type bridge girders. The applicability of all these developments were demonstrated by failure load tests on full-scale prototype units of the girder family using an exclusive loading platform built on the storage area of the manufacturer. The developed bridge girder family already has CE marking.

Peer-review under responsibility of the scientific committee of the Creative Construction Conference 2023.

Keywords: bridge girder, bonded and unbonded post-tensioning, fibre reinforced polymer, self-compacting concrete, digitalization.

1. Introduction

To strengthen cooperation between academic research and economy, the Competence Center on Safety Science and Technology has been established at BME in 2021 in frame of the 2019.1.3.1-KK-2019-00004 project by the National Research, Development and Innovation Office. The aim of the project is to manage and optimize the risks occurring in the typical operational areas of the construction industry by applying a safety-oriented approach that meets the needs of the profession and the achieved technological level. The project joints research effort of the BME and the cooperating potential industrial partners in fields of the oil and gas industry, the mission critical systems in vehicle and traffic safety and the building industry as well as aims to develop the necessary IT platform including the technologies of AI, IoT, Big Data.

The building industry branch of the project is represented by the cooperation of the BME Faculty of Civil Engineering and the ZÁÉV and divided into two subprojects. One initiates novel product developments and related technological improvements in production and, hereby, aims progress in field of traffic safety. The other focuses on construction industry process management by making developments related to the construction industry digitalization and thus, increase the safety level of the construction industry services. In both fields, the planned developments are realized by combining the competences of the BME Faculty of Civil Engineering and the ZÁÉV in the given area. The primary location of these developments is the precast concrete plant of ZÁÉV in Bóly.

This paper introduces the results and progress of the first subproject that has completed the first two out of the three milestones until the end of 2022.

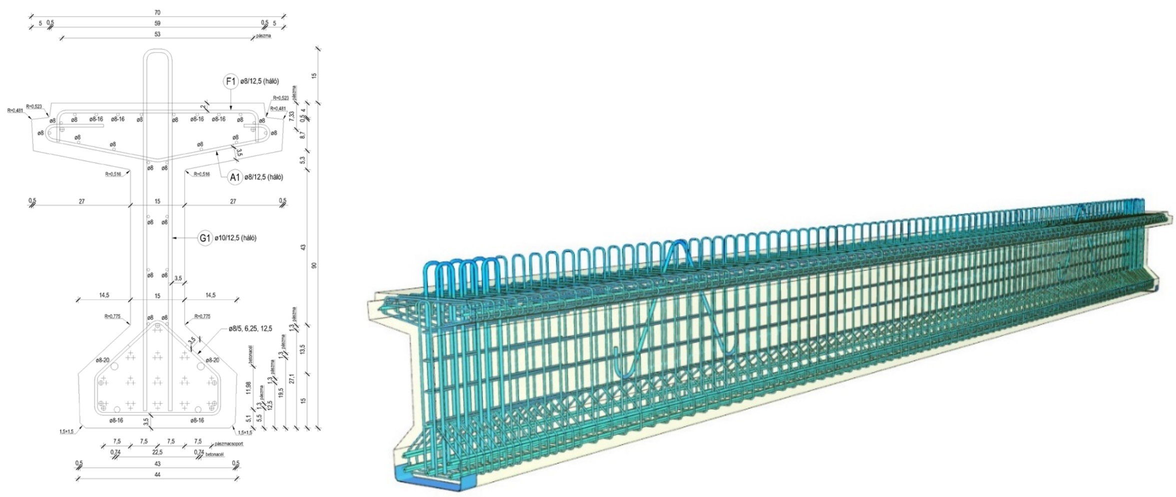
2. Development of bridge girders using new technologies

The main goal of this subproject was to develop a bridge girder family applicable in bridges as well as other related prototype bridge girders by using new technologies that are unique both in the domestic and the foreign bridge girder industry. The following three milestones were set as result items:

- Milestone 1. (2021) Development of a new, marketable precast bridge girder family with traditional straight line pre-tensioning and made of self-compacting concrete
- Milestone 2. (2022) Development of prototype precast bridge girders an related prototype bridge superstructures using the combination of traditional straight-line, factory made pre-tensioning and several types of post-tensioning
- Milestone 3. (2023) Development of durable prototype precast bridge girders using fiber reinforced polymer (FRP) bars as embedded reinforcement

Bringing the developed new bridge girder family to market within the frame of the project was set as a TRL9 indicator in the Competence Center project. Thus, several activities above research and design tasks had to be completed to make the product marketable.

Using bridge girders developed until Milestone 1 as basic units, high performance prototype bridge girders either suitable for meeting higher structural or durability demands or containing unique structural and technological solutions compared to ordinary applications were developed until Milestone 2 & 3. The primary purpose of these developments was to exploit the applicability of these new technologies. Thus, they are going to be developed to the level of a prototype product but are not intentionally moved to the market. Using self-compacting concrete for these prototype beams help further improving the related concrete technology already developed until Milestone 1.



(a) (b)

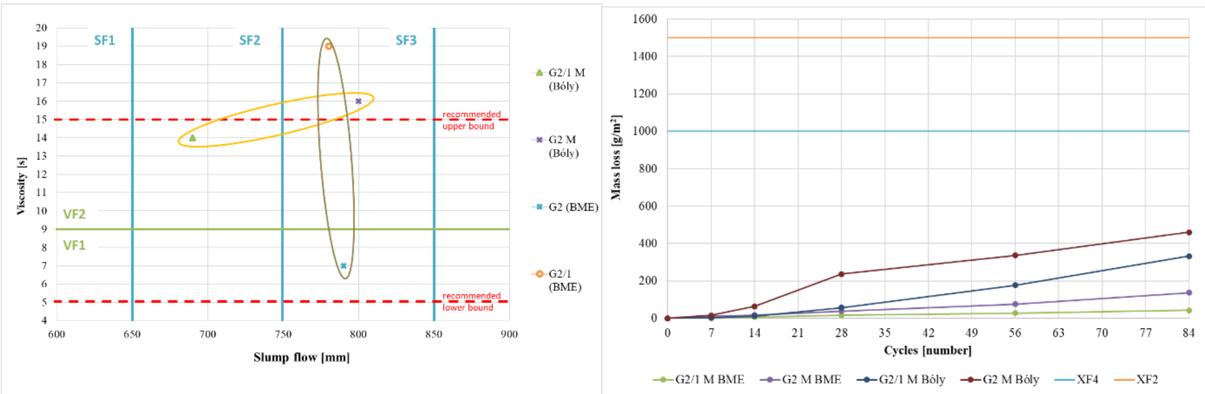
Fig. 1. (a) Cross-section and (b) 3D view of the ZBI-90 type bridge girders.

2.1. Development of a new precast bridge girder family with traditional straight line pre-tensioning and made of self-compacting concrete (Milestone 1)

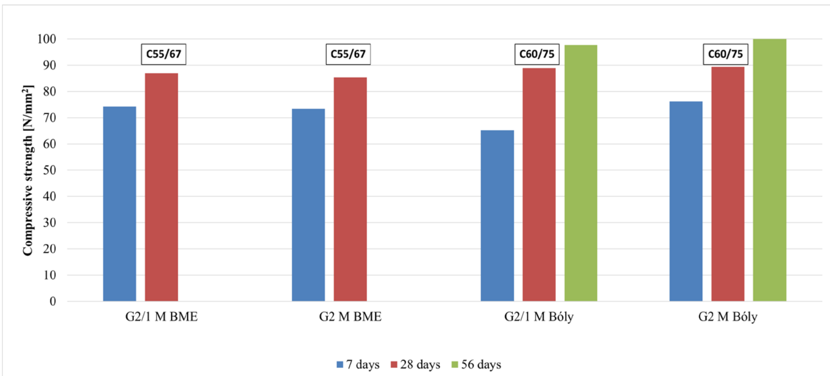
A family of prefabricated, high-performance bridge girders (ZBI-90) with a factory-made straight-line pre-tensioning and made of self-compacting concrete with a height of 0.9 m and a length range of 8.8-26.8 m has been developed (Fig. 1). Ordinary prestressing and reinforcing steel was applied as reinforcement. Safety-wise, the bridge girder family represent a reliability level that fully complies with the Eurocode and, consequently, the technical regulations for roads and associated road bridges to be introduced in Hungary in 2024 and the already operative MÁV regulations for railway bridges. To support designers in applying these products in new design projects, a product catalogue (design manual) on the structural details of the girder family as well as "sample" production plans of each element with subsequent lengths of 1 m are under elaboration.

2.1.1. Concrete design

To reduce energy and time consumption during production, high performance self-compacting concrete instead of traditional normal weight concrete has been implemented into the manufacturing process. Its applicability has been demonstrated for years in building construction. Several mixtures of self-compacting concrete containing normal aggregate and one or combination of four types of additions (limestone powder, basalt powder, CEM III type cement, metakaolin) were elaborated and then optimized through several laboratory and production site mixings. The optimization focused primarily on the consistency of fresh concrete ensuring workability (Fig 2(a)) and those hardened concrete properties which are determinant on durability (Fig. 2(b)). The target strength class was set as C50/60 (Fig. 2(c)). As result, two recipes containing limestone powder (G2) and CEM III type cement (G2/1) were selected, tested both in laboratory and on factory site and then further optimized (to G2 M and G2/1 M) when an alternative aggregate (sand) supplier was contracted. The initial tests on factory produced G2 M and G2/1 M mixtures ended in 2023 Q1.



(a) (b)



(c)

Fig. 2. Results of (a) consistency (b) freeze-thaw and (c) compressive strength tests of the developed concretes.

The developed high-performance self-compacting concretes satisfy the durability requirements for environmental classes XC4-XD3-XF4(H) which describe the most severe possible environmental exposures (atmospheric corrosion effects, freeze-thaw attack and chloride penetration from de-icing salt) occurring during the intended 100 years long design working life of bridges. Because the recent technical specifications did not allow the use of the elaborated high amount of additions in structural concrete, the modification of the related road technical regulation e-ÚT 07.02.11 was also initiated.

2.1.2. Load tests on prototype beams

To test the structural adequacy of the developed girders, four 10.80 m long prototype beams made of the most promising developed concrete mixes were manufactured in factory building conditions.

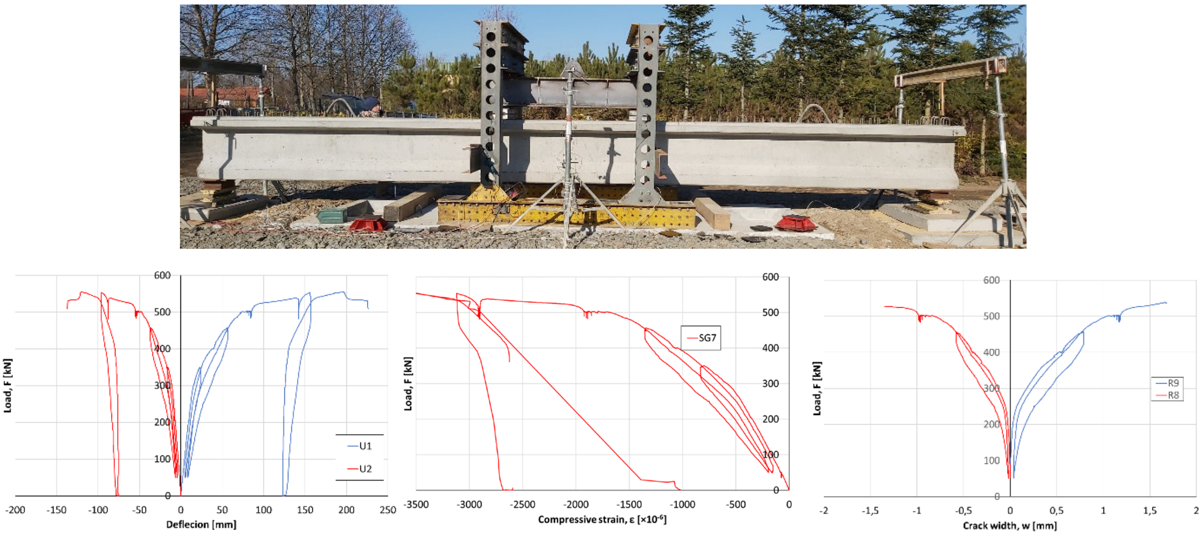


Fig. 3. Test arrangement and the measured results for the load test of a prototype girder.

After concrete hardening these beams were load tested until failure on the loading platform of the factory (see Sec. 3) During the full loading process the relevant structural parameters (deflection, compressive and tension strains and crack width) of the beams as function of the applied load were simultaneously registered with a digital data acquisition system (Fig 3). Typical bending failure occurred as expected.

2.1.3. CE marking

Based on the evaluation of the initial tests of the developed self-compacting concretes as well as those of the completed load tests of prototype beams, the competent certification body issued the Factory Production Control Certificate (CE license) for the manufacturer declaring that both the developed self-compacting concretes as constituent materials and the developed ZBI-90 bridge girder family were complying with the relevant European standards and ready to trade them on the European market.

2.2. Development of prototype precast bridge girders an related prototype bridge superstructures using the combination of traditional straight-line, factory made pre-tensioning with several types of post-tensioning (Milestone 2)

Post-tensioning has been widely used for long time on its own in many fields of construction industry. The aim of this development was to combine the structural advantages of post-tensioning with pre-tensioning. Within this period of the project two pairs of bridge girders of Milestone 1 were equipped with two types of post-tensioning.

2.2.1. Prototype beams and prototype superstructures

As part of this, the traditional, straight-line, factory-made pre-tensioning technology was combined in one version with a straight-line, **i**nternally placed, **unb**onded post-tensioning (iub), while in the other version, with a curved, **i**nternally placed, **b**onded post-tensioning (ib). Two 10,80 m long products were produced from both versions (Fig. 4 (a) and (b)).

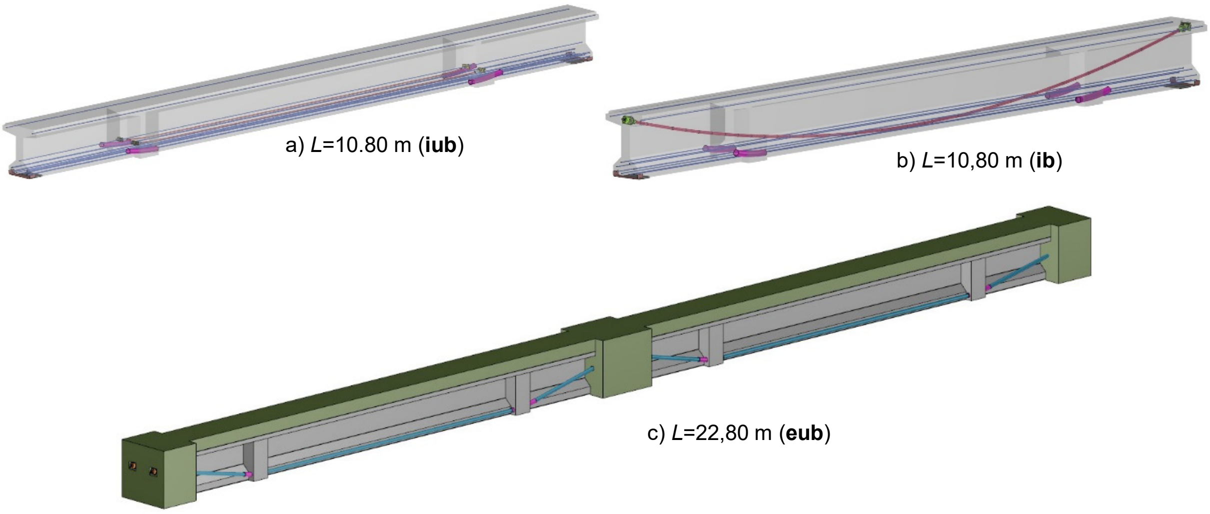


Fig. 4. Internally post-tensioned prototype beams (“iub” and “ib”) and the externally post-tensioned prototype structure (“eub”).

Then, in accordance with the usual arrangement of continuous bridge superstructures comprising of series of precast beams, these pairs were assembled subsequently in longitudinal direction and structurally connected with monolithic concrete top flange of 20 cm thickness to produce a composite, two-span continuous prototype structure. Thereafter, these prototype structures were equipped with a polygonal, **e**xternally placed, **u**n**b**onded post-tensioning (eub) (Fig. 4 (c)).

2.2.2. Challenges in structural design and manufacturing

During design it was extremely challenging to determine the necessary amount and the time of stress release as function of concrete age for both types of prestressing during the manufacturing process as well as to numerically follow the structural effects of each type of prestressing on both the concrete product and each other.

In order to form places to deviate the external tendons and to anchor the „iub” tendons, it was inevitable to locally modify the geometry of girders by designing two collar-like blocks positioned symmetrically along the length of each prototype girder. The formwork of these deviation blocks had to be individually produced and included as supplementary parts into the existing formwork system used in Milestone 1.

2.2.3. Testing the prototype structures

The prototype structures were built above the loading platform and positioned such that one span could be loaded until failure (Fig. 5). The general process of these tests such as the loading and measuring system as well as the applied test protocol and the evaluation process were similar to those used for the Milestone 1 girders (Sec. 2.1.2) with appropriate changes in load intensity.

Fig. 5. Testing the “eub” type prototype structure and typical damage places at failure.

2.3. Development of durable prototype precast bridge girders using fiber reinforced polymer (FRP) bars as embedded reinforcement

In this part of the project, following the international trends [1]-[2], the structural applicability of recent technologies presumably suitable for extending the design working life (above 100 years) of concrete bridge girders subjected to extreme environmental effects under normal service conditions are focused. Many of these solutions are not yet elaborated to a level which makes them compatible with recent standards but are hot research topics of this field.

One of these technologies aims improving the durability of concrete members by replacing the traditional mild steel reinforcement with glass (GFRP) or basalt-based (BFRP) fibre reinforced polymer bars in order to avoid steel corrosion. For bridge girders this would lead to significant loss in stiffness therefore, an unbonded post-tensioning system with a factory-made corrosion protection which completely separates steel components from the concrete environment is designed as part of the hybrid reinforcement of the prototype bridge girders to be developed until Milestone 3. The biggest challenge of this development is to structurally harmonize the mechanical properties of FRP bars with the structural behaviour of bridge girders to comply with the relevant design requirements. A particular difficulty is that many types of FRP products available on the market are not quality certificated. Thus, laboratory testing will be inevitable to experimentally determine the mechanical properties that play a key role in structural design and behaviour.

The testing of these prototype bridge girders with hybrid reinforcement is expected until the end of 2023.

3. Technological modernization of the equipment

An integral part of the project was directed to the technological modernization of the participants' accessories. Beside the acquisition and installation of new assets in the BME Materials Testing Laboratory for research and educational purposes and in the factory buildings to improve the effectivity of the manufacturing process, one of the major investments, in close relation to the developed bridge girder product, was made on a brand new, complete formwork system also equipped with heat curing facilities. Of this, a 60 m long set was purchased at the expense of the project for trial productions and for the production of the prototype beams, while an additional 150 m required for continuous production after the physical completion of the project under market conditions will be covered by the ZÁÉV from its own resources.

As another investment of the project, a loading device (loading platform) was built at the production site together with the related energy supply and assess paths. This platform consists of a concrete bench as foundation lowered into ground, a steel loading frame and a 2×1000 kN capacity hydraulic loading equipment that make it suitable for 1:1 scale load tests of all products manufactured in the plant (as shown in Fig. 3). This allows either making experimental tests for research and development purposes or conducting presentations for marketing purposes or expanding the portfolio with market-based leasing. The loading equipment is fully compatible with that of the BME Structural Testing Laboratory, thus, it enables further research or project-based cooperation with BME.

Acknowledgements

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References

[1] D. Whitmore, "Extending the Service Life of Existing Concrete Structures to Last Beyond 100 Years," MATEC Web of Conferences, Vol 364. p. 04025, 2022, doi: 10.1051/matecconf/202236404025.

[2] Modjeski and Masters, Inc, "Bridges for Service Life Beyond 100 Years: Service Limit State Design," Strategic Highway Research Program 2 Report S2-R19B-RW-1, 2014, ISBN 978-0-309-43375-4, doi: 10.17226/22441.

REACHING NEW HEIGHTS IN THE USE OF CONCRETE PREFABRICATED PREFINISHED VOLUMETRIC CONSTRUCTION (PPVC) : TWO 56-STOREY RESIDENTIAL TOWERS IN SINGAPORE

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Abstract

To reduce the reliance on foreign workforce and raise construction productivity, the Singapore building industry is encouraged to embrace the concept as per Design for Manufacturing and Assembly (DfMA) [1] whereby a substantial portion of construction works is done off-site in a controlled manufacturing environment. Prefabricated Prefinished Volumetric Construction (PPVC) modular system is one such technology that significantly reduces on-site manpower requirement and speed up construction. This paper outlines the pioneering & innovative PPVC technology of using a patented reinforced concrete composite structural wall system for construction of two 56-storey residential towers. Prototype sample tests such as compression test and shear tests had been carried out to verify the performance of this wall system; the test results show that this sandwiched combined wall system is able to perform under the actions of bending and shear in a composite manner satisfactorily. This development is currently the world's tallest residential building project constructed using the reinforced concrete modular construction technology.

Keywords: prefabricated prefinished volumetric construction, reinforced concrete composite structural wall system.

1. Introduction.

The Avenue South Residence is a residential high-rise development at Silat Avenue in Singapore. The project comprises two tower blocks of 56-storey apartments with ancillary landscape, a swimming pool and communal facilities at ground level. A multi-storey car park is included with a basement level linking the two towers. In total, there are 505 residential units in the development.

To further enhance construction productivity, the Singapore Urban Redevelopment Authority (URA) encourages the building industry consultants and builders to adopt the Prefabricated Prefinished Volumetric Construction (PPVC) technology, which is an advanced and highly productive construction methodology that speeds up construction works significantly.

With support from BCA and working in tandem with the builder, TW-Asia Consultants Pte Ltd has pioneered the design of the reinforced concrete PPVC technology using its patented **Composite Structural Wall system** under the European Patent no. EP3263795 entitled "Composite Structural Wall and Method of Construction Thereof". It was through research, testing and continual development that this unique structural wall system was devised as the key technical component for the PPVC system.

The Avenue South Residence is currently the tallest building project in the world adopting the reinforced concrete PPVC modular system when its last module was installed in January 2022. The previous height record was for 40 storey building [2, 3].

2. Architectural Constraints

As part of the planning design requirement, pocket sky gardens and a refuge floor (Fig. 1a & 1b) are required to be provided in the two towers as follows:

- 16 nos. of pocket gardens at different levels of the tower
- Refuge floor at 36th storey of the towers

These constraints have resulted in the discontinuity of PPVC module adoption at these floors/areas. Consequently, this has impacted the construction efficiency & productivity as these affected areas are constructed in conventional in-situ methods which are more labour intensive.

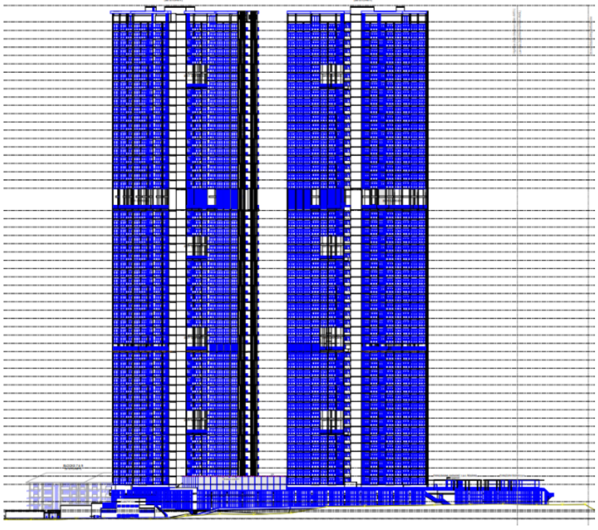

Fig. 1a. Pocket gardens and refuge floor

Fig. 1b. Close-up view of pocket gardens

3. Structural System

The super structure comprises mainly the two 56- storey high towers with two basements and two podium storeys of car park. The foundation system for the two towers and the podium comprises bored piles. The basement two slab is formed by pile raft whilst flat slab system is adopted for basement 1, 1st & 2nd storey. Beam slab system is adopted for 3rd storey.

The superstructure for the two tower blocks adopts the RC PPVC modular system for a minimum 65% of floor area in compliance with BCA's Code of Practice on Buildability, 2015 [4]. The remaining floor areas, which are mainly at the corridors, comprise conventional precast/in-situ RC beams and slabs linking the PPVC modules to the lift and staircase storey shelter cores. The corridor floor structures provide an effective connection to transfer lateral loads from the PPVC modules to the core walls.

4. PPVC System

4.1. PPVC Module – Weight Constraint

The weight of PPVC module is a major consideration in the transportation logistics and lifting operation. The module weight is designed to a minimum considering the tower crane lifting capacity & coverage. In particular, high strength concrete is used for the module walls to minimize its thickness according to design requirement.

4.2. PPVC Modularisation

Generally, the size and dimensions of the PPVC modules is controlled by the local transportation constraint and hoisting capacity of tower cranes.

In compliance with local road requirements & to avoid the need for auxiliary police escorts, the width of modules is to be contained within a 3.4m overall transport vehicle width (including load). The height of modules (including trailer bed) should also be considered if the transportation route involves passing below overhead bridges and gantries with height clearance of 4.5m.

Additionally, site access and loading/unloading areas need to be studied properly for the truck delivery, manoeuvrability, temporary storage on site and hoisting of the modules for the final installation.

To maximise productivity, ease of module prefabrication, site connectivity and installation, the PPVC module modularisation should take account of the following factors:

- Modules shape should be rectilinear as much as possible
- Module wall thicknesses should be uniform and standardized as much as possible
- The walls within each module should be aligned as much as possible

The **Avenue South Residence** used a total no. of 3034 of PPVC modules in the project

PPVC modularization plan for Tower 1 & 2 is shown in Fig. 2 below.

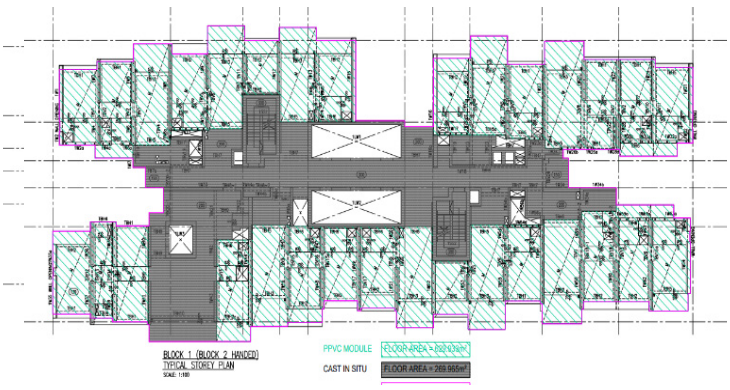

Fig. 2. Tower 1 & 2 PPVC Modularization Plan

4.3. PPVC Concrete Carcass Components

A typical PPVC concrete carcass (Fig. 3a & 3b) comprises two structural shear walls, a floor slab, a non-structural ceiling slab and non-structural end wall with window opening. The M&E services conduits and pipes are embedded in the floor slab, ceiling slab and walls of the module.

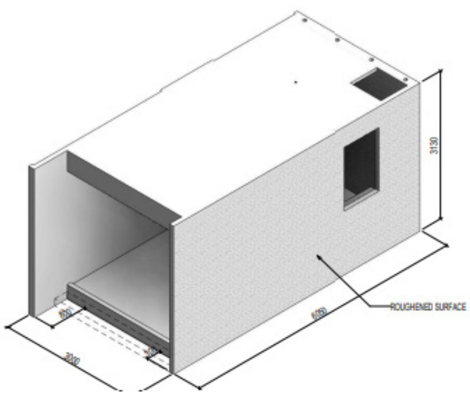

Fig.3a. Typical PPVC concrete carcass

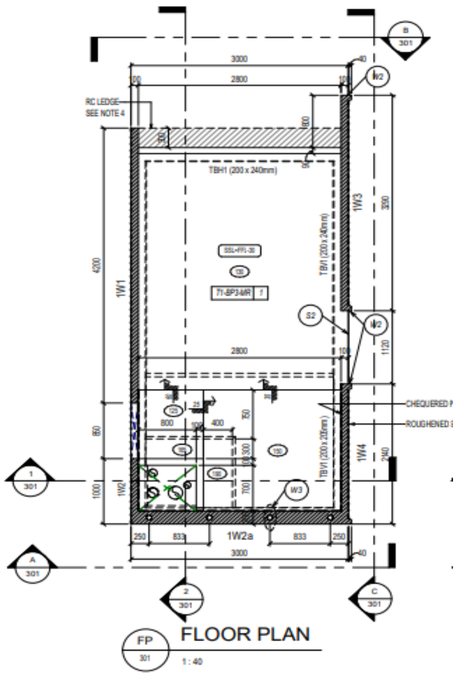

Fig. 3b. Typical PPVC module floor plan

4.4. Floor Slab

The RC floor slab spans across to the module walls is working as a horizontal diaphragm, transferring lateral loads to the lift and staircase shelters core walls.

4.5. Ceiling Slab

The ceiling slab is considered as a non-structural slab to provide rigidity to the module and help to brace the walls during transportation and installation; it also acts as a working platform during the module installation process.

4.6. RC Walls

Generally, the structural RC walls are located along the two long sides of the modules; designed to support the ceiling and floor slabs. Once installed, these walls are connected to adjacent module's walls via reinforcement embedded in self-levelling concrete within the joints to form a sandwiched composite structural wall. The sandwiched wall system is designed to behave in a composite manner under compression and bending actions. Thus, all the module walls are load-bearing and participate in the lateral load-resisting mechanism of the whole building.

4.7. Horizontal Floor Diaphragm

Horizontal floor diaphragm action is achieved by connecting the adjoining PPVC modules' walls and slabs together with in-situ concrete & reinforcement. The linking modules are connected to the in-situ floor slabs and lift/storey shelter core walls with adequate reinforcement anchorage.

5. Tower Lateral Load Performance

5.1. Wind Tunnel Test

Wind tunnel test had been carried out to obtain more accurate estimates of the wind-induced structural loads, load effects and building motion of the two tower blocks.

The results of the wind tunnel study indicate that the one-year return period peak building acceleration & rotational velocities and the five-year period standard deviation building satisfy the relevant published occupant comfort criteria for wind-induced building motions.

5.2. Lateral Analysis

ETABS [5] software has been used to model the performance of the tower blocks under lateral load. The building's top displacement and inter- storey drift ratios are controlled to be less than 1/500 and the ETABS results show that the tower structures perform satisfactorily.

The performance of the towers under wind loads are shown in Table 1 & 2 below:

Table 1. Lateral displacement under wind action

Lateral Displacement	Block 1/2
Total building top displacement ration, **δ / H**	1/652 ≥ 1/500
Inter storey drift ration, **δ** / h	1550 ≥ 1/500

Table 2. Mode shape – time period (s)

Mode	Block 1/2
1 (Translational)	7.2
2 (Translational)	6.6
3 (Torsional)	6.1

According to the analysis:

- Along the major axis of the PPVC composite shear walls ~ 85% of wind is carried by the walls
- Along the minor axis of the PPVC composite shear walls ~ 30% of the wind is carried by the walls

5.3. Tower Robustness

Tower block robustness has been checked under notional horizontal loads such that the blocks are capable of resisting a notional design ultimate horizontal load applied at each floor or roof level simultaneously equal to 1.5% of the characteristic dead weight of the structure between mid-height of the storey below and mid-height of the storey above in accordance with local design standards.

Structural ties, such as horizontal floor ties and vertical ties are provided and checked to comply with local design standards.

6. Durability

The structures have been designed to Structural Class S4 (Design working life of 50-years) with Exposure Class XC3 (Corrosion induced by carbonation - moderate humidity) to local design standards.

7. Fire Resistance

The structures have been designed for a fire resistance of 1.5 hours. Fire compartmentalization is achieved by separation of floor slabs, separation of vertical compartments by RC walls or rated partitions and plumbing risers located within the PPVC units. Horizontal compartmentalization is maintained with the risers segmented into separate compartments at each floor.

8. PPVC Wall Prototype Load Tests

Prototype tests had been carried out to study the behaviour of the sandwiched composite wall under the actions of compression and bending. The objective of the load tests was to verify whether the composite wall sample could withstand the design load in a composite manner.

9. PPVC Concrete Carcass Fabrication and Fit-Out Work

3-D fabrication method was adopted for the casting of the module concrete carcass in Johor, Malaysia. The following critical activities and checking were carried out in the precast factory. The completed PPVC concrete carcasses from Malaysia were delivered to a fit-out factory in Singapore. The level of finishing and fittings to be completed off-site are as per the Code of Practice on Buildability 2015 [2].

10. PPVC Installation on Site

Following module delivery to site, a heavy-duty tower crane with self-adjusting lifting frame was used to hoist the modules to their final position in installation. The main challenge during installation was the possible swaying of modules at height due to wind load. Experienced crane operator plays an important role in ensuring the PPVC module is lifted slowly and carefully so that the module is not tilting during hoisting and final positioning. The surface of the concrete slab receiving the modules has to be checked for levels; the platform receiving the module may be adjusted and levelled with shin plates where required. The modules would then be installed with reference to the surveyed gridlines marked on the receiving slab or top slab of the lower modules installed previously.

Tower crane location & lifting coverage analysis have to be planned in advance so that it is suitably positioned considering the reach and lifting capacity (Fig. 14). The logistic route/space of module delivery, off-loading and temporary storage on site must also be taken into consideration for smooth delivery, lifting & final installation.

M&E services between the adjoining modules were connected; light fittings, equipment & fixtures were installed. Final Architectural activities: floor finishes, painting, door leaves, wardrobe, cabinet doors were also completed during this stage.

External water seepage control at the PPVC modules end joints generally comprises applying a layer of fibre mesh and cementitious water-proofing membrane.

For this project, the total duration of PPVC module installation was approximately 18 months; with the floor cycle time from six to nine days. Understandably, the first two to three floors took a longer cycle time as they were in the initial learning curve of installation.

11. Buildable Design & Constructability Score

Based on local guidelines in BCA's Code of Practice on Buildability 2015 [2], by adopting the PPVC technology, this project has achieved a marked improvement in the Buildability and Constructability Score. The total Buildable Design Score achieved is 94, which is higher than the minimum required score of 88. The total Constructability Score is 64, which is higher than minimum required score. The photo of the completed towers is shown in Fig. 4

Fig.4. Photo of the completed towers

12. Conclusion

This project has successfully implemented the RC Composite Shear Wall System as the PPVC technology in the construction of the two 56- storey residential towers in Singapore.

Advantages realised from the adoption of PPVC system in this project were as follows

- Improved productivity and hence early project completion
- Improve site safety as on-site activities are reduced tremendously
- Improved quality of end product as most activities are done in a factory-controlled environment
- Vast reduction in noise & dust pollution at job site

Acknowledgements

The authors gratefully acknowledge the involvement and support of all the project team members who have contributed one way or another to the successful completion of this project.

References

[1] Singapore Building and Construction Authority (2023) “Design for Manufacturing and Assembly (DfMA)” [Online] https://www1.bca.gov.sg/buildsg/productivity/design-for-manufacturing-andassembly-dfma (Accessed: June 2023)

[2] Wong S et al, “Concrete Prefabricated Prefinished Volumetric Construction for Two High-rise Blocks in Singapore”, The Structural Engineer, August 2021, pp 28-35

[3] Wong S et al, “Case Study: The Use of Concrete Prefabricated Prefinished Volumetric Construction for Two Blocks of 40-Storey Residential Flats (The Clement Canopy), Singapore”, IABSE Congress, Feb 2021, New Zealand

[4] Building and Construction Authority Singapore, “Code of Practice on Buildability 2019 Edition”, [Online] https://www1.bca.gov.sg/docs/default-source/docs-corp-news-and-publications/publications/for-industry/buildability-series/cop-on-buildability-2019.pdf?sfvrsn=d8526675_0 (accessed Jun3, 2023)

[5] Computers & Structures, Inc. (2021) ETABS [Online] Available at: www.csiamerica.com/products/etabs (Accessed: July 2021)

RECYCLING OF SPENT FLUID CATALYTIC CRACKING CATALYST IN CEMENTITIOUS COMPOSITES

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Abstract
One of the approaches to reduce CO_2 emission generating by cementitious industry is to use supplementary cementitious materials (SCMs). Fluid catalytic cracking (FCC) catalyst is a material used in oil-refining processes, showing high chemical activity. Spent FCC catalyst, which disposal is mainly limited to landfilling, providing considerable environmental risk and utilization costs, can be considered as a promising pozzolanic material using as a cement substitute. In present paper cement pastes with the use of spent FCC catalyst as a partial cement substitute within the range of 0-25%, were prepared and studied regarding both their fresh and hardened-state performances. Tests included slump flow, compressive strength, flexural strength and water absorptivity in the case of cement pastes. The results showed that the aforementioned properties of cement pastes prepared with its appropriate addition were found to be comparable with the adequate of plain cement ones. It is worth mentioned that such applicability of spent refinery catalyst might ensure numerous benefits both for construction and petrochemical sector, contributing to sustainable development.

Keywords: cement pastes, oil refinery wastes, spent fluid catalytic cracking catalyst, supplementary cementitious materials, sustainable development.

1. Introduction

The modern world without concrete is hard to imagine as it is currently the second most consumed material, after water, worldwide [1]. However, there is a considerable environmental impact behind the development of modern infrastructure which concrete made possible. The manufacturing of ordinary Portland cement (OPC), most popular binder in concrete technology, is responsible for 5-8% of all man-made CO_2 emission to the atmosphere [2]. Therefore, the need to shape sustainable development in building engineering is indisputable [3-4]. One of the approaches to reduce this CO_2 emission is to use supplementary cementitious materials (SCMs) [5]. These might be various by-products and waste materials from agriculture and industrial activities. In terms of being capable of partially replace cement in the concrete binder blend efficiently, SCMs need to possess pozzolanic properties, i.e. consist of alumina-silicates and possess high specific surface area. One of the promising material for such applicability seems to be spent fluid catalytic cracking (FCC) catalyst. This material is widely used in petrochemical industry, showing high chemical activity in the FCC process, a crucial process for fuels production. After losing its sufficient activity, this material becomes waste. According to the paper [6], worldwide petrochemical industry generates 400,000 metric tons of spent FCC Catalyst, most of which is sent to landfills. Unfortunately, such procedure provides not only high utilization cost for the petrochemical business but, most notably, considerable environmental pollution and health risk. It is therefore that spent FCC catalyst comprises chemical contaminants, including heavy metals (such as Cr, Pb, Ni), adsorbed from the oil fraction it processed [7]. However, as mentioned in the paper [7], those pollutants might be efficiently bound in the hardened structure of cementitious composites, which minimizes the risk of their release to the natural environment. Considering the above, the present research aims to preliminary evaluate if it is possible to partially replace cement with the use of spent FCC catalyst derived from Polish oil-refinery company. For this purpose, the primary cementitious composites, i.e. cement pastes, were prepared with the addition of spent FCC catalyst, substituting cement within the range of 0-25%, by mass. The water to binder (w/b) ratio of 0.40 was used to prepare the mixes. To evaluate the impact of the catalyst addition, all cement paste mixes and their respective cured samples were investigated regarding performances in the fresh and hardened state, respectively.

2. Materials and methods

2.1. Materials characteristic and cement paste mixes formulations

The spent FCC catalyst was derived from the FCC unit of Polish oil-refinery company. It was investigated as a partial substitute of cement (CEM I 52.5R). The chemical composition of spent catalyst and cement, obtained using X-ray fluorescence spectrometer analysis (XRF) and from [8], respectively, has been presented in Table 1. Accordingly, spent FCC catalyst is mainly composed of SiO_2 and Al_2O_3.

Table 1. Chemical composition of the materials used in research.

Material \ Oxide	SiO_2	Al_2O_3	CaO	Fe_2O_3	MgO	SO_3	Others
Cement [wt. %]	20.09	4.84	64.02	3.87	1.15	2.83	3.20
Spent FCC catalyst [wt. %]	44.48	38.11	-	-	3.43	3.88	10.10

The constituents were mixed together with water in the laboratory bowl, mentioning that spent catalyst was used as a cement substitute within the range of 0-25%, by mass. The mixes were described as follows: 0.40 X%, where 0.40 corresponds to the w/b ratio while X corresponds to the cement substitution level. The plain cement mix (without spent catalyst) was named as a reference one and described as 0.40 ref. The formulations of mixes have been listed in Table 2.

Table 2. Formulations of 1 dm^3 of cement paste mixes.

Material \ Mix (1 dm^3)	0.40 ref	0.40 5%	0.40 10%	0.40 15%	0.40 20%	0.40 25%
Cement [kg]	1.374	1.301	1.229	1.157	1.086	1.015
Spent FCC catalyst [kg]	0.000	0.068	0.137	0.204	0.272	0.338
Water [kg]	0.550	0.548	0.546	0.545	0.543	0.541

2.2. Evaluation of the fresh-state performances of cement paste mixes

The fresh-state performances of cement paste mixes were evaluated through the flow table test, according to the PN-EN 1015–3:2000. The truncated cone-shaped mold was placed on the spreader disc and the cement paste mix was applied in two layers, thickening each for at least 10 strokes of the compactor. Then, the excess paste was scraped off and, after 15 s, the mold was slowly removed by lifting it vertically. After shaking the disc 15 times, two diameters of the mix oriented perpendicularly to each other were measured. Their average value was assumed as a final flowability value of the mix.

2.3. Evaluation of the hardened state performances of the cement paste samples

The following performances of cement paste samples prepared from each paste mix were determined:

- Compressive strength (CS). The tests were determined on 40 × 40 × 40 mm cubic cement paste samples, both at 7th and 28th curing day, on the electromagnetic universal testing machine with a load cell capacity of 300 kN.

- Flexural strength (FS). The tests were determined on 40 × 40 × 160 mm beam cement paste samples, both at 7th and 28th curing day, on the same machine as for the CS measurement.
- Water absorptivity. The tests were determined on cement paste samples through the following subsequent sequence of action. The mass ‘A’ of cement paste sample was measured after removing all uncombined water through drying the sample to a constant weight. Subsequently, the sample was placed in the vessel with water. Immediately after the sample was removed from the vessel, its surface was carefully dried with a cloth. After that, the mass ‘B’, corresponding to the maximum saturated cement paste sample, was measured. Finally, the water absorptivity was calculated as the difference between B and A in relation to A and expressed in percentages.

3. Results

3.1. Results of the fresh-state performances of cement paste mixes

The results of flowability tests carried out on each cement paste mix in the fresh state have been presented in the Fig. 1. It might be noticed that the slump flow values of cement paste mixes with the addition of spent FCC catalyst as a cement substitute until 15% were found to be comparable with the 0.40 ref mix, mentioning that the flowability of 0.40 5% and 0.40 10% mixes increased. However, mixes with higher amount of spent catalyst in the binder blend, i.e. 0.40 20% and 0.40 25%, revealed deterioration of the flowability. The lowest value of slump flow was obtained for 0.40 20% and equaled 187.5 mm, while the highest one was obtained for 0.40 10% with average slump diameter of 250.0 mm.

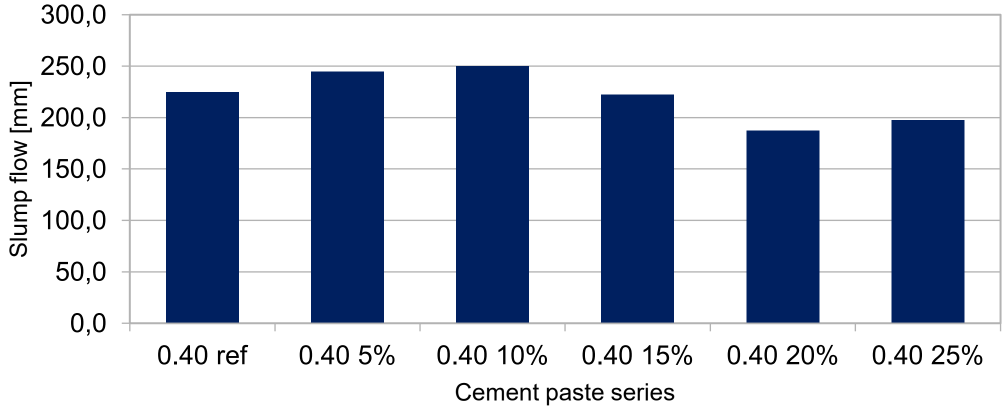

Fig. 1. Results of flowability tests of cement paste mixes.

3.2. Results of the hardened state performances of cement paste samples

- Compressive strength (CS). The results of CS tests have been presented in the Fig. 2. It might be noticed that the 7 days CS values were found to be higher for samples with the addition of spent FCC catalyst as a cement substitute until 10%. However, samples with higher amount of spent catalyst in the binder blend, i.e. 15% and more, revealed linear deterioration of 7 days CS while compared with 0.40 ref. The 28 days CS values were found to decrease with the increase of spent catalyst addition in the binder blend, mentioning that these values were comparable with 0.40 ref when no more than 15% of cement was substituted. The 0.40 25% samples showed more significant decrease of 28 days CS. The 0.40 5% sample revealed the highest value of 7 days CS, i.e. 41.5 MPa, exceeding 0.40 ref for 8%. The highest value of 28 days CS was obtained for 0.40 ref sample (51.3 MPa).

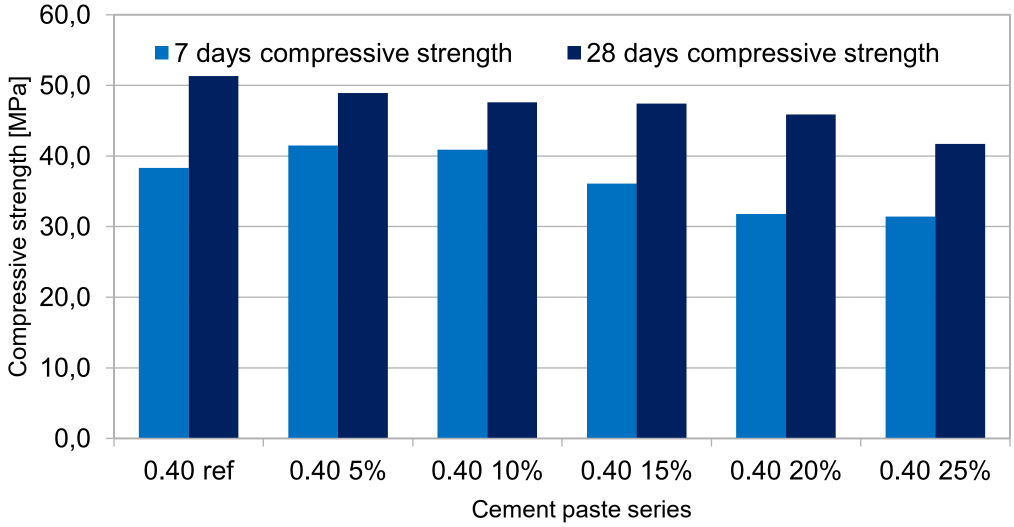

Fig. 2. Results of compressive strength tests of cement paste samples.

- Flexural strength (FS). The results of FS tests have been presented in the Fig. 3. It might be noticed that both 7 and 28 days FS values were found be same or comparable with the 0.40 ref, while no more than 10% of cement was substituted with spent FCC catalyst. However, samples with higher amounts of catalyst addition, i.e. 0.40 15%, 0.40 20% and 0.40 25%, revealed more significant both 7 and 28 days FS deterioration, mentioning that their values were found to be comparable between these 3 series of samples. The samples with the highest 7 days FS values, from these with spent catalyst addition, i.e. 0.40 5% and 0.40 10%, showed the deterioration of FS for 4%, while compared with the 0.40 ref sample (9.20 MPa). The sample with the highest 28 days FS, i.e. 0.40 10%, revealed the same FS value as the 0.40 ref sample (11.0 MPa).

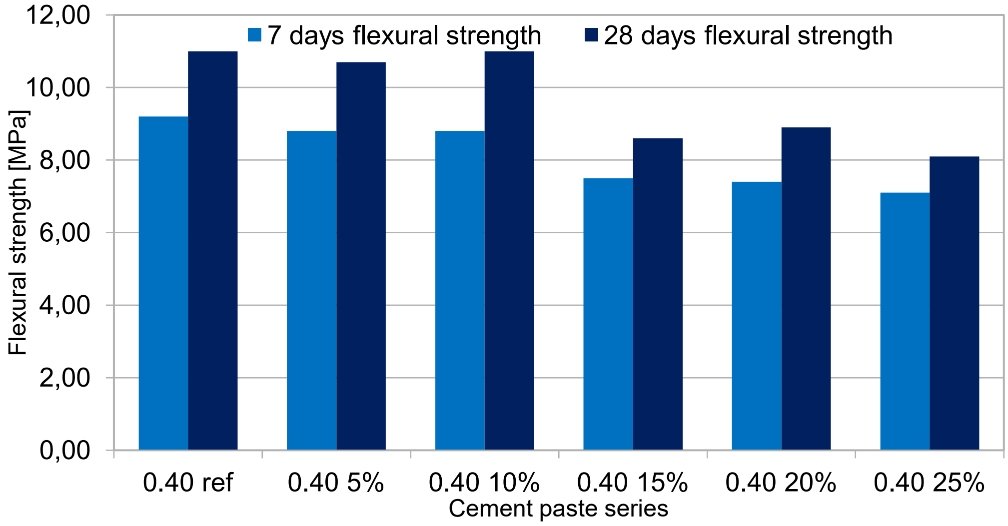

Fig. 3. Results of flexural strength tests of cement paste samples.

- Water absorptivity. The results of water absorptivity tests have been presented in the Fig. 4. It might be noticed that the water absorptivity generally tended to increase with the increase of cement substitution level. The water absorptivity values obtained for samples with up to 15% addition of spent catalyst, despite being higher than 0.40 ref, might be comparable. However, water absorptivity values of 0.40 20% and 0.40 25% were significantly higher while compared with each of the remining samples. The highest water absorptivity was obtained for 0.40 20% and equaled 29.59%.

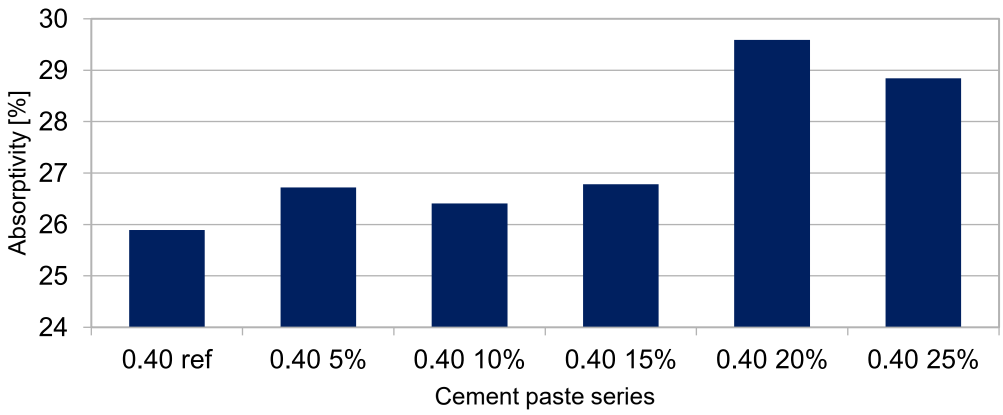

Fig. 4. Results of water absorptivity tests of cement paste samples.

4. Discussion

The negative effect provided by spent FCC catalyst on the flowability of cement paste mixes, which was observed for higher cement substitution levels, i.e. 20% and 25%, might be generally attributed to the high specific surface area of spent catalyst. This provides its high water demand and reduces the amount of available water in the system and hence the flowability of mixes. Such results are in accordance with a number of papers, e.g. [9-11]. This effect was not observed while spent catalyst was substituted up to 20% of cement in the binder, probably due to high w/b ratio of 0.40, which was used in this research.

The development of 7 days CS, similarly to slight decrease of 28 days CS values, mentioning that this decrease was lower than the respective cement replacement level would indicate, for cement paste samples with of up to 10 – 15% of cement substitution, might be attributed to the pozzolanic activity of spent FCC catalyst. Such behavior of this material is promoted by its properties, i.e. aluminosilicate chemical composition and high specific surface area. The pozzolanic activity of spent FCC catalyst has been investigated in many papers, such as [12]. As such, the spent catalyst possess the ability to react with $Ca(OH)_2$ (direct calcium hydroxide consumption of 1540 mg per 1 g of spent catalyst) in the presence of moisture to form additional CSH gel in the system and hence developing strength performances [12]. The deterioration of CS of cement paste samples with higher amount of spent catalyst, i.e. 20% and 25%, might be caused by the dilution effect, i.e. cement content reduction, which predominates over pozzolanic activity of the material, when it substitutes higher amount of cement.

The deterioration of FS of cement paste samples, when 15% and more of cement was substituted, is in accordance with results obtained by the Authors on cement paste samples with different w/b ratio, i.e. 0.30 [13]. Accordingly, this phenomenon might be attributed to the porous structure of cement paste samples containing spent FCC catalyst caused by the interphase transition zone (IZT) between CSH gel and unreacted spent FCC catalyst particles with the lack of adhesion between them [13].

The results of water absorptivity of cement paste samples indicate that spent FCC catalyst addition promotes absorptivity, especially when it substitutes 20% and more of cement in the binder. This finding is in accordance with the paper [7]. Again, it might be caused by the tendency of those samples to dry up, as the spent FCC catalyst, as a high water demanding material, promotes vital adsorption of water.

Overall, spent FCC catalyst was found to be a promising substitute for up to 15% of cement in cement pastes, when the w/b ratio is 0.40. The resulted pastes exhibited comparable or slightly deteriorated properties both in the fresh and hardened state, acceptable from the construction materials viewpoint, while compared with the plain cement paste. It should be pointed out that the performances of cement pastes with the addition of spent FCC catalyst are slightly deteriorated while compared with the adequate ones of pastes obtained by the Authors in previous research, when the w/b ratio of 0.30 was used [13]. Nonetheless, it is worth mentioned that such addition of spent FCC catalyst enables the reduction of cost and environmental impact of cementitious composites whilst, simultaneously, dissolves the problem of waste management in petrochemical sector. Such results underlined the correctness of further research on the applicability of spent FCC catalyst derived from Polish petrochemical industry in cementitious composites, which are planned to be performed by the Authors in the case of more advanced composites, i.e. cement mortars, and with the use of some other oil-refinery waste materials.

5. Conclusions

- Spent FCC catalyst obtained from Polish oil-refinery might be considered as a promising partial substitute of cement for the production of more environmental friendly construction materials characterized by lower prices, CO_2 emission and natural resources consumption.
- According to the results of current research, spent FCC catalyst, while substituting up to 15% of cement in cement pastes prepared with w/b ratio of 0.40 exhibited comparable or slightly deteriorated performances while compared with the reference, plain cement paste.
- The formulations of cement paste mixes with the incorporation of spent FCC catalyst, i.e. w/b ratio and cement substitution level, significantly influence their fresh-state performances, as well as mechanical strength and water absorptivity of respective hardened composites.
- More extensive research are planned to be performed by the Authors in the case of cement mortars. Apart from spent FCC catalyst, it is planned to investigate some other petrochemical wastes, i.e. spent Claus catalysts and waste ceramic balls from molecular sieves, regarding such applicability.
- The recycling of oil refinery wastes from petrochemical industry is common with circular economy approach and, if achieved, would provide a massive feedstock for construction industry thereby being vital business injection contributing to the collaboration and mutual development of those two sectors.

Acknowledgements

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References

[1] D. M. Petroche and A. D. Ramirez, “The Environmental Profile of Clinker, Cement, and Concrete: A Life Cycle Perspective Study Based on Ecuadorian Data,” Buildings, vol. 12, no. 3, p. 311, Mar. 2022, doi: 10.3390/buildings12030311.
[2] Wei, J., & Cen, K. (2019). Empirical assessing cement CO2 emissions based on China's economic and social development during 2001–2030. Science of the Total Environment, 653, 200-211.
[3] Czarnecki, L., & Deja, J. (2021). Zrównoważone budownictwo; w poszukiwaniu przemiany prometejskiej. Inżynieria i Budownictwo, 77.
[4] L. Czarnecki and D. Van gemert, “Innovation in construction materials engineering versus sustainable development,” Bulletin of the Polish Academy of Sciences Technical Sciences, vol. 65, no. 6, pp. 765–771, Dec. 2017, doi: 10.1515/bpasts-2017-0083.
[5] M. S. Imbabi, C. Carrigan, and S. McKenna, “Trends and developments in green cement and concrete technology,” International Journal of Sustainable Built Environment, vol. 1, no. 2, pp. 194–216, Dec. 2012, doi: 10.1016/j.ijsbe.2013.05.001.
[6] B. Alonso-Fariñas, M. Rodríguez-Galán, C. Arenas, F. Arroyo Torralvo, and C. Leiva, “Sustainable management of spent fluid catalytic cracking catalyst from a circular economy approach,” Waste Management, vol. 110, pp. 10–19, Jun. 2020, doi: 10.1016/j.wasman.2020.04.046.
[7] N. Su, Z.-H. Chen, and H.-Y. Fang, “Reuse of spent catalyst as fine aggregate in cement mortar,” Cement and Concrete Composites, vol. 23, no. 1, pp. 111–118, Feb. 2001, doi: 10.1016/s0958-9465(00)00074-3.
[8] “Cement Foreign Trade” http://www.musayapi.com.tr/index.asp (Access date: 30.11.2022).
[9] N. Su, H.-Y. Fang, Z.-H. Chen, and F.-S. Liu, “Reuse of waste catalysts from petrochemical industries for cement substitution,” Cement and Concrete Research, vol. 30, no. 11, pp. 1773–1783, Nov. 2000, doi: 10.1016/s0008-8846(00)00401-4.
[10] J. Payá, J. Monzó, M. V. Borrachero, and S. Velázquez, “Cement equivalence factor evaluations for fluid catalytic cracking catalyst residue,” Cement and Concrete Composites, vol. 39, pp. 12–17, May 2013, doi: 10.1016/j.cemconcomp.2013.03.011.
[11] S. Nunes and C. Costa, “Numerical optimization of self-compacting mortar mixture containing spent equilibrium catalyst from oil refinery,” Journal of Cleaner Production, vol. 158, pp. 109–121, Aug. 2017, doi: 10.1016/j.jclepro.2017.04.161.
[12] A. M. Matos, S. Nunes, C. Costa, and J. L. Barroso-Aguiar, “Spent equilibrium catalyst as internal curing agent in UHPFRC,” Cement and Concrete Composites, vol. 104, p. 103362, Nov. 2019, doi: 10.1016/j.cemconcomp.2019.103362.
[13] P. Niewiadomski and M. Cisiński, “The Impact of Waste Fluid Catalytic Cracking Catalyst Addition on the Selected Properties of Cement Pastes,” 10th MATBUD’2023 Scientific-Technical Conference, Feb. 2023, doi: 10.3390/materproc2023013010.

THE EFFECTS ON COST, TIME, AND ACCURACY WHEN USING UNMANNED AIRCRAFT SYSTEMS TO MEASURE SLOPED EXCAVATIONS

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Abstract
As uses for unmanned aircraft systems (UAS) continue to evolve, opportunities for research to validate improvements in cost, time, and quality become crucial. Specifically, there have been many studies focused on how UASs can simplify the measurement of earthwork quantities, but is there a compromise in the accuracy of the measurements for a reduced effort to obtain them? The objective of this research was to identify if such a compromise exists. This study measured the amount of effort (cost and time) to obtain a level of accuracy (quality) that is consistent with the traditional measurements obtained with ground-based robotic surveying equipment. The researchers performed a quantitative experiment using twelve measurement check points across a one-acre test site (4,047 m^2). The test site was sloped to simulate a level of complexity that would be consistent with a more challenging area of a typical construction project site when obtaining earthwork quantities. The methodology involved measuring three separate UAS flights with differing flight paths and image gathering overlaps and comparing this to a ground-based measurement procedure. An accuracy analysis was conducted on the location of the twelve check points. Time and cost data were computed for all procedures and compared. This study found that not all flight path techniques met industry standards for accuracy while others did. The tradeoff when using the more accurate flight paths was a longer time to obtain and process data. When the overall cost was considered, it was determined that the UAS-based measurement approach was less expensive – resulting in a mixed determination about whether a "compromise" existed. This study further elaborates on the findings and proposes recommendations about how this comparison benefits innovation in the built environment.

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Keywords: efficiency, site work, survey, uas, construction.

1. Introduction

Sloped excavations are common on most construction projects. Sometimes a sloped excavation is for underground pipe or utilities, and other times it is a part of the landscape or for drainage. In order to accurately measure the slope of the excavation, a survey is needed. Among the traditional surveying methods, the robotic total station has become the predominant method of surveying in construction. Traditional methods involve employees trained in surveying using fairly expensive equipment. Because of the cost and time required for traditional surveying, many contractors may be inclined to skip the excavation measurements. Lack of measurements can result in poor quality or even unsafe working conditions.

1.1. Background and rationale

If using a UAS to measure sloped excavations is accurate enough to maintain a safe jobsite and support project quality, this method could save the contractor both money and time. Topographic drone measurements may not be as accurate as traditional survey methods but may be accurate enough to replace traditional survey methods for certain applications. Due to the high cost of state of the art surveying equipment, general contractors typically subcontract surveying activities. Many projects are already using drones on the jobsite for other purposes such as job progress photo documentation. Using drones for this application could expand the current uses of drones with minimal additional equipment cost.

1.2. Purpose

The purpose of this research is to investigate the accuracy, cost, and time associated with using UAS's to measure sloped excavations compared to traditional surveying methods. The key objectives include investigating current methods of measuring slopes, assessing the accuracy of UAS measurements, and identifying the cost and time involved for both methods.

1.3. Scope

The scope of this research uses sloped excavations ranging from 5 to 20 feet. These excavations were measured using both a robotic total station and UAS. The accuracy, time, and cost impacts of using UAS for topographic and slope measurements compared to using a robotic total station was analysed.

2. Literature Review

A study was conducted concerning the current uses of drones in the construction industry and the associated costs. This study found that 70% of contractors use drones to capture aerial images for project management and documentation purposes. It also found that 82% of companies believe drones are a useful tool for project progress documentations [1]. With many construction companies already using drones for documentation purposes and the high approval rating of drone usage, UAS should be rapidly adopted by the remaining construction companies not yet using drones.

2.1. Traditional Slope Measurements using a robotic total station

The slope of an excavation can be determined by many different methods, but the most prominent is using a robotic total station. A robotic total station is surveying equipment that combines electronic distance measurement and automatic target recognition [2]. This equipment can be operated remotely and has been proven to be accurate and effective in monitoring and measuring slopes [3]. One of the main advantages of using a total station is the simplicity of collecting data. After data collection is complete, the data can be processed to determine the absolute coordinates [2]. Another advantage of using a robotic total station to measure sloped excavations is the accuracy of the instrument. Robotic total stations have been proven to be extremely accurate and capable of measurements within 0.5 mm of the actual location [4].

The main disadvantages include the initial cost, lines of sight, environmental factors, and maintenance [2]. A reference point must be set to give the robotic total station a baseline for data collection [4]. Access to all measurement points and reference points must be available to collect the data [3]. This means that, if a slope is too steep and cannot be easily walked on, using a robotic total station may not be possible. Even with the high accuracy and advantages of using a robotic total station, other methods may be simpler and more convenient.

2.2. UAS Alternative

One alternative to robotic total stations is using a UAS to measure sloped excavations. Since the creation of drone technology, many different types of drones have been developed. The size of the site, altitude of the flight, and data collection time are the main factors to consider when choosing a drone to measure a sloped excavation. This investigation used a DJI Mavic 2 Pro drone, a quad copter, and Pix4D software for data processing.

2.3. UAS Photogrammetry

Data captured by a single drone flight can now be used by a computer program to create a three-dimensional model of the built environment. One study evaluated the accuracy of georeferenced three-dimensional models created using UAS photogrammetry [5]. Precision was calculated using control points scattered around the test site, and the drone was able to measure these positions with a variance of 4 mm horizontally and 10 mm vertically [5].

The measurement accuracy of UAS photogrammetry has been studied in other applications. Millimeter accuracy was obtained during the experiments of one study. Many conditions must be met to ensure this level of accuracy, including that the control and survey points must be numerous, the lighting must be optimal, and the aircraft must be stable. The experiments also took significant time due to the large number of photographs needed to measure accurately [6]. The main finding of the study was the high measurement accuracy that can be obtained using UAS photogrammetry.

2.4. UAS Topographic Mapping and Measurements

Research has also been conducted on the accuracy of UAS topographic mapping on large sites. One study assessed the accuracy of UAS-based surveys using 18 missions on a 3.5 acre site using two different drones [7]. Root Mean Square Error (RMSE) was used to calculate the accuracy of the topographic measurements. RMSE is measured by finding the number of pixels for each checkpoint. RMSE values less than one pixel are considered to be highly accurate, values between one and three pixels are moderately accurate, and any value greater than three pixels is said to have a low level of accuracy. This study’s results found that all RMSE values were under two pixels for all eighteen missions. Higher accuracy was obtained with a higher resolution camera and flight paths taking the photos from a lower altitude [7].

A similar study was conducted on an even larger site of 4.942 acres. The experiment for this study created digital terrain models (DTM) [8]. This model uses color to show changes in elevation. This study focused on the effects of changing the amount of overlap in the photos taken with front image overlaps of 70%, 80%, and 90%. The side lap percentages used in this study were 50%, 60%, and 70%. RMSE was used to analyze the high-resolution topographic [8]. These results show that using an 80% front image overlap and 50% image side lap resulted in the most accurate measurements in the x, y, and z coordinates. The flight with the least accurate results used an 80% front image overlap and 70% image side lap.

Another study was conducted on how the number of ground control points affects the accuracy of topographic measurements collected using UAS [9]. The results of the experiment showed that the error statistics were very similar regardless of the number of ground control points [9]. This study showed that a limited number of ground control points can produce acceptable results for many geotechnical applications.

2.5. Data Acquisition

Most research on the accuracy of UAS topographic mapping has employed the autonomous flight mode of the drone by pre-planning the flight on software such as Pix4D. Most UAS’s have Global Positioning System (GPS) navigation capability that allows for autonomous take-off, navigation, and landing with the flight path following a pre-programmed pattern along with automatic camera operation. The flight programming software takes into account the area being surveyed, the amount of picture overlap desired, and the altitude above ground to be flown. Autonomous flights are able to collect asymmetrical images with the same overlap and side lap percentages on each flight. This greatly improves the image acquisition and photogrammetry process [10].

This study also investigated the effect of different flying altitudes on the accuracy of topographic measurements in easting directions, northing directions, and elevation. The findings clearly show that the most accurate results come from lower flight altitudes. As the altitude increases, the accuracy decreases in a linear relationship [10]. The impact of image quality was also included in the experiment. Pix4D software has three kinds of point cloud densification options including low, optimal, and high-quality modes. The findings showed that the higher resolution point clouds resulted in slightly more accurate measurements, but high-quality mode takes much more time to process the images and stitch them together. It is recommended to use high-quality images if a lot of vegetation is present [10]. Gridding is a critical parameter that can impact the accuracy of UAS-based topographic surveys. There are two main categories of gridding: single and double gridding. Using a double grid should increase the number and quality of images, but it can greatly increase processing time and cause more error sources. It is recommended to use a single grid for UAS-based topographic mapping [10].

2.6. Research Gaps and Limitations

All research to date on the accuracy of UAS topographic measurements has focused on large sites using a variety of UAS types, flying altitudes, photogrammetry software, image overlap, image quality, flight modes, and gridding systems. Accuracy assessments of UAS on sites less than half an acre or on a specific slope have not been widely researched. The cost and time impacts of UAS topographic measurements compared to robotic total stations have not been studied. Because of the potential for substantial cost and time savings using a UAS, because contractors may likely have a readily available UAS already being used onsite, and would be more likely to measure sloped excavations even on small construction sites, and because of the importance of these measurements to construction safety and construction quality, a systematic comparison of topographic measurements of slope by UAS versus robotic total stations in terms of accuracy, time requirements, and cost could be valuable to the construction industry.

3. Research Methodology

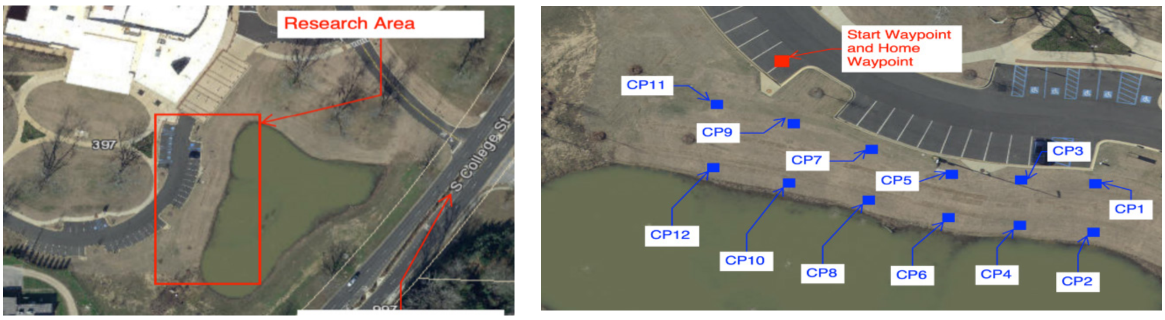
This research study consists of four phases. The first phase is experiment preparation, the second phase is data acquisition, and the third phase is data processing. The fourth and final phase includes the results and analysis of all data collected.

3.1. Phase 1: Preparation

3.1.1. Checkpoint Establishment

A slope feeding into a water retention area was selected as the experimental area for this research study. Wood survey stakes were driven into the ground at each of these points to ensure that they are clearly visible in the images collected from the drone. The stakes and hubs are not needed to measure the slope of the hill at the experimental site, but they will be used to ensure the topographic measurements of the robotic total station and UAS are from the exact same location. Refer to Figure 1 below.

Fig. 1. (a) Experiment Location, (b) checkpoints



3.1.2. Flight Planning

The flight plans will be created using the Pix4DCapture application on a smartphone. The Pix4DCapture application is used to program flight information based on flight pattern, location, flight altitude, angle of the camera, front overlap, side overlap, and drone speed. After all the settings are selected, the flight plan is created by drawing a 'fence' around the area to be flown. This can be seen in Figure 2 below. This application can then be connected to the UAS controller to autonomously fly the set location and collect aerial images according to the programed settings.

Fig. 2. Programmed Flight Path

Three flights were planned. All used a 75 foot altitude, 80% front overlap, and fast drone speed. Experiment 1 used a single grid pattern (as shown above) and 50% side overlap. Experiment 2 used a single grid with 70% side overlap, and experiment 3 used a double grid (not shown but a second grid perpendicular to the single grid) with 70% side overlap. These were the configurations chosen for this study.

3.2. Phase 2: Data Acquisition

To determine the accuracy of the topographic measurements obtained from the UAS, accurate three dimensional coordinates of all checkpoints were obtained using a robotic total station – a Trimble RPT600 was used. For time comparisons, the total station was set up, measured all checkpoints, and taken down 3 separate times and the activity timed with a stop watch. This was included in later analysis.

The drone used to fly the programmed flight and collect the photo images was a Mavic 2 Pro. During each of the three experiments, a stop watch was used to measure the time it took to plan the flight, set up the drone, fly the mission, pack the drone back into its case, upload and process the data. Each of these time categories were recorded separately for later analysis.

3.3. Phase 3: Data Processing

Digital image processing was used to combine the digital images collected during each UAS flight into one model. Digital image processing is the stitching together and manipulation of digital images completed by software on a computer. Pix4DMapper was the software used to process the images. A densified point cloud is then created by using a set of three-dimensional coordinate points that reconstruct the images together [11]. The software is able to generate digital surface models and orthophotos. From these models, digital terrain models and contour maps can be created to determine three-dimensional coordinates at all checkpoints throughout the research area.

3.4. Phase 4: Results and Analysis

3.4.1. Accuracy and Slope Assessment

Root Mean Square Error (RMSE) is used by the American Society of Photogrammetry and Remote Sensing (ASPRS) for assessing three-dimensional coordinate accuracy [11]. The horizontal and vertical accuracy will be measured by comparing the coordinates of each checkpoint with the coordinates from the same point measured by the robotic total station. The RMSE values of horizontal and vertical measurements will be compared to the horizontal accuracy standards for orthophotos and the vertical accuracy standards for digital elevation data from ASPRS. Table 1 shows the horizontal tolerance for different classes of horizontal measurements obtained by orthophotos and the tolerance of vertical accuracy for elevation measurements in vegetated areas (ASPRS Accuracy Standards for Digital Geospatial Data, 2015).

Table 1. Horizontal and Vertical Accuracy Classes (additional classes not shown – refer to ASPRS document)

Horizontal Class	RMSE Values (cm)
I	Pixel Size x 1
II	Pixel Size x 2
III	Pixel Size x N

Vertical Class	Vegetated Vertical Accuracy (cm)
I	2.9
II	7.4
III	14.7

3.4.2. Time and Cost Assessment

To assess the time impacts of using UAS to measure sloped excavations, duration must be accurately recorded for each step of topographic measuring. During the data acquisition phase, the time spent on the UAS checkpoint measurements and robotic total station checkpoint measurements were recorded three times for each experiment.

Cost is a major factor for many construction companies. Saving money is essential to maximize the profit on each project. To compare the cost of using UAS versus robotic total stations to measure sloped excavations, the cost of labor will be compared. The labor cost will be measured by using the average time spent on each experiment multiplied by an hourly labor rate. A one person survey crew with a robotic total station was given an hourly rate of $225. This was assumed to be subcontracted. The hourly rate for the UAS crew considered a UAS pilot at $53 per hour with one visual observer at $41 per hour. These were assumed to be employed by the contractor.

4. Data Analysis

This section discusses the results of UAS-based sloped excavation measurements using photometric surveys for each experiment.

4.1. Horizontal, Vertical, and Slope Measurements

The photogrammetry model for each of the three experiments were processed with Pix4DMapper software to create an orthomosaic model and a digital surface models as shown in Figure 3 below.

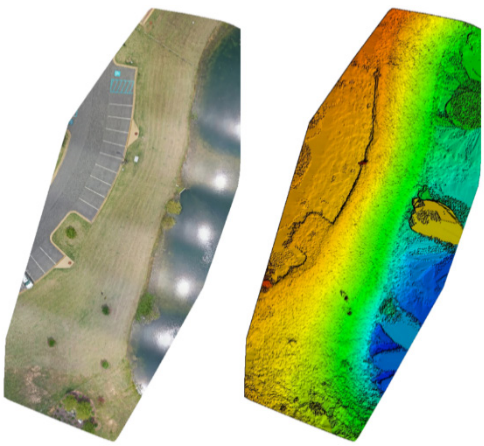


Fig. 3. Orthomosaic Model (Left) and Digital Surface Model (Right) from Experiment 1

Any point in the orthomosaic model can be selected to give the calculated three-dimensional location obtained from the drone flight. The horizontal distances, vertical distances, and slope measurements obtained in UAS experiments were compared to the same data from the robotic total station to find the delta in each measurement. These deltas were used to calculate the RMSE by taking the square root of the sum of the measurements in the horizontal direction, vertical direction, and slope and dividing by the count of the measurements.

4.2. Accuracy Comparison

The UAS-based distances measured in the three experiments were compared to the same distances calculated from the robotic total station. This comparison used RMSE to determine the accuracy of the UAS-based photometric values with the assumption that the values collected by the robotic total station were precisely correct. The RMSE values were computed in centimeters to simplify comparison to the accuracy standards for digital elevation data. The RMSE values can be seen in Table 2 below.

Table 2. RMSE Values and Horizontal / Vertical Data Accuracy Classes

	Horizontal RMSE (cm) (Class)	Vertical RSME (cm) (Class)	Slope RSME (cm)
Experiment 1	42.623 (XVII)	74.562 (VII)	0.090
Experiment 2	10.369 (V)	24.693 (IV)	0.035
Experiment 3	5.877 (II)	3.956 (II)	0.006

Using UAS photogrammetry models from experiment 1, the horizontal and vertical measurements were not consistent or accurate. In this case, the measurements did not meet the industry standards for accuracy. While Experiment 2 was more accurate horizontally, this scenario did not reach an acceptable of accuracy.

Experiment 3 used a double grid flight plan with 80% forward overlap and 70% side overlap at a flying altitude of 75 feet and was the most accurate of the three experiments. The horizontal and vertical measurements were consistent and accurate due to the increased number of photographs used to produce the orthomosaic model. The horizontal measurements ranged from 1.949 to 7.987 centimeters off of the measurements obtained from the robotic total station. The vertical measurements were incorrect by a range of 0.132 to 7.234 centimeters. In this case, alternate hypothesis 1 proved to be true. The application of UAS in measuring sloped excavations did reach an acceptable accuracy class of the ASPRS Accuracy Standards for Digital Geospatial Data in experiment 3. The RMSE values for experiment 3 were significantly lower because of the number of images collected to produce the orthomosaic model.

4.3. Time Comparison

The time spent on data collection and processing for each experiment was measured with a digital stopwatch and recorded. The data collection phase was split into setup time, data collection time, and disassembly time. The breakdown of times can be seen in Table 3 below. The 3 robotic total station timings were so close, only the average time for each category is shown in the table.

Table 3. Time Comparison (min:sec)

	Setup	Data Collection	Disassembly	Data Processing	Total Time
RoboticTotal Station	8:08	10:07	3:18	13:54	34:27
UAS 1	3:50	3:17	1:22	61:05	69:34
UAS 2	3:32	3:28	1:14	75:15	83:29
UAS 3	3:48	8:13	1:14	118:46	131:01

The total time using the UAS was much longer than the average robotic total time. In the data collection phase the drone was able to collect the data faster than the robotic total station. This relative efficiency of the drone in data collection is due in part to the longer times required to set up and take down the robotic total station and also due to the extensive amount of walking to each checkpoint in order to get the measurements. The Trimble RPT600 used a Panasonic tablet that was able to record the data and export them into an Excel file. The Excel file simply had to be saved on a flash drive and loaded onto a computer. This made the processing stage quick and easy. The majority of time in data processing for UAS was Pix4DMapper processing the images to create the orthomosaic and digital surface models. Once these models were created however, locating each checkpoint was as simple as clicking on the survey hub and recording the three-dimensional coordinates. In all, application of the UAS in measuring sloped excavations took more time compared to using a robotic total station to measure the slope.

4.4. Cost Comparison

The total time spent in each experiment to measure the slope at the experimental location was used to find the associated cost. The total time spent was multiplied by the hourly rate of an appropriate worker to calculate the cost of performing the slope calculations in each experiment. The cost calculations can be seen in Table 4 below.

Table 4. Slope Measurement Cost

	Hourly Rate - Operator	Hourly Rate – Visual Observer	Time (hours) - Operator	Time (hours) – Visual Observer	Total Cost
RoboticTotal Station	$225	N/A	0.59	N/A	$132.75
UAS 1	$53	$41	1.16	0.14	$67.26
UAS 2	$53	$41	1.475	0.14	$83.95
UAS 3	$53	$41	2.2	0.22	$125.08

The average cost for the robotic total station to measure the sloped excavation was $131.25. All three UAS experiments cost less than using a robotic total station. This proves alternate hypothesis 3 to be true. The application of UAS in measuring sloped excavations reduced the cost compared to using a robotic total station to measure the slope. However, the most accurate UAS measurements were obtained from UAS experiment 3, and the cost of this experiment was $125.68 because the double grid flight plan required more time to capture the additional images and to process the additional associated data. This cost was only slightly less than that of all three robotic total station experiments. If the measurement accuracy of a double grid flight plan is needed in order to use UAS to measure sloped excavations on construction sites, there will not be as much cost savings relative to robotic total station measurements.

4.5. Discussion

The results of the three UAS experiments differed because the varied flight parameters affected the number of orthophotos collected in each experiment. The number of orthophotos affected the detail of the orthomosaic and digital surface models created from Pix4DMapper and the time required to process the images.

5. Conclusions and Recommendations

In this research study, the results varied between the different experiments conducted with the UAS in measuring a sloped excavation. The accuracy of UAS experiments 1 and 2 did not meet industry standards, while experiment 3 did meet the accuracy standards. In all three experiments, UAS-based slope measurements took more time when compared to a robotic total station, but UAS-based slope measurements also cost less when compared to a robotic total station. Given the differing results of each experiment, there is much to be learned about measuring slopes with drones.

However, the time for data processing was a significant factor in the UAS calculations which was compounded by counting operator hours for this process. It should be noted that the majority of data processing time is the time taken for the computer program to run which can be done unattended once it is set up. Making adjustments for this would significantly reduce the cost of the UAS operations.

5.1. Conclusions

The inaccuracy of slope measurements using UAS in this study ranged from 5.877 to 42.623 centimeters in the horizontal direction and ranged from 3.956 to 74.562 centimeters in the vertical direction. The major inconsistencies were derived from the different flight plans used in each experiment. The main correlation found in this study was that the most accurate slope measurements were produced by the UAS flight plan that collected the largest number of images. The most accurate experiment used a double grid flight plan with 80% forward overlap and 70% side overlap. This flight collected 151 images.

In short, this research shows that, with certain flight plans, UAS's could be used to accurately measure sloped excavations and save money when compared to using a robotic total station. Using a UAS should not be viewed as a replacement for traditional survey methods but another option to measure slopes. The application of a UAS would be very beneficial if a robotic total station is not available within the needed time frame, if the slope is steep, or if the slope is hard to traverse.

5.2. Recommendations for Further Study

The first recommendation would be to use the double flight grid on multiple experiments to determine the consistency of UAS slope measurements. On a much larger site, the data collection time could be much longer using a robotic total station. If this is the case, UAS could save significant time in measuring sloped excavations. Another recommendation is to complete a similar study utilizing a drone other than the DJI Mavic 2 Pro and a different software program than Pix4D to determine the impacts on accuracy, time, and cost. This future research could define more precisely the parameters when using UAS to measure sloped excavations would be the most beneficial to the construction industry.

References

[1] N. Blinn and R.R.A Issa, "Feasibility Assessment of Unmanned Aircraft Systems for Construction Management Applications". Construction Research Congress 2016, 2593–2603, doi: 10.1061/9780784479827.258.

[2] D Cook, "Robotic Total Stations and Remote Data Capture: Challenges in Construction". Geotechnical News, Vol. 24 No.4,December 2006, pp 42-45

[3] T.B. Afeni and F.T. Cawood, "Slope Monitoring using Total Station: What are the Challenges and How Should These be Mitigated?" South African Journal of Geomatics, 2(1), 41–53, https://doi.org/10.4314/sajg.v2i1

[4] J. Zhou, B. Shi, G. Liu and S. Ju, "Accuracy analysis of dam deformation monitoring and correction of refraction with robotic total station". PLOS ONE, 16(5), e0251281, doi: 10.1371/journal.pone.0251281.

[5] S. Barba, M. Barbarella, A. Di Benedetto, M. Fiani, L. Gujski and M. Limongiello, "Accuracy Assessment of 3D Photogrammetric Models from an Unmanned Aerial Vehicle". Drones, 3(4), 79, doi: 10.3390/drones3040079.

[6] K. Cmielewski, P. Gołuch, J. Kuchmister, I. Wilczynska, B. Cmielewski and O. Grzeja, "Detection of crane track geometric parameters using UAS. Automation in Construction", 128, 103751, doi: 10.1016/j.autcon.2021.103751.

[7] J. Burgett, B. Lytle, D. Bausman, S. Shaffer and E. Stuckey, "Accuracy of Drone-Based Surveys: Structured Evaluation of a UAS-Based Land Survey". Journal of Infrastructure Systems, 27(2), 05021005, doi: 10.1061/(ASCE)IS.1943-555X.0000605.

[8] M. Muhammad and K.N. Tahar,"Comprehensive Analysis of UAV Flight Parameters for High Resolution Topographic Mapping". IOP Conference Series: Earth and Environmental Science, 767(1), 012001, doi: 10.1088/1755-1315/767/1/012001.

[9] E. Stott, R.D. Williams and T.B. Hoey, "Ground Control Point Distribution for Accurate Kilometre-Scale Topographic Mapping Using an RTK-GNSS Unmanned Aerial Vehicle and SfM Photogrammetry. Drones", 4(3), 55, doi: 10.3390/drones4030055.

[10] H.H. Aliand F.M. Abed, "The impact of UAV flight planning parameters on topographic mapping quality control". IOP Conference Series: Materials Science and Engineering, 518(2), 022018, doi: 10.1088/1757-899X/518/2/022018.

[11] R.Q. Ismael and Q. Z. Henari, "Accuracy Assessment of UAV photogrammetry for Large Scale Topographic Mapping". 2019 International Engineering Conference (IEC), 1–5, doi: 10.1109/IEC47844.2019.8950607

VALUE ENGINEERING FOR PERFORMANCE IMPROVEMENT OF SUSTAINABLE CONSTRUCTION PROJECT

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Abstract

The technology of value engineering (VE) can be used to provide project owners with the required optimum value that is characterized by the project being delivered at the lowest cost and at a greater level of performance and quality. Providing this value can be challenging or near impossible at certain instances that could eventually impair some basic and important principles of VE that are key in arriving at the required goals of a project. This paper assessed the available conventional VE standard(s) with the aim of improving its ability to provide the best value to project owners especially in sustainability or green building projects. A critical review of the available VE tools and their uses in construction projects led to a discovery that project owners always emphasized reducing the cost of projects at the initial stages and sometimes during the whole life cycle of projects. This was identified as a limiting characteristic of the conventional VE that could hinder the project and VE team from performing VE exercises that meet the value requirements of projects. Performance worth (PW) VE approach was used to address this limitation in the function identification and analysis phase of the VE methodology. Construction industry VE practitioners were provided with a presentation and then surveyed about the conventional VE and PW approaches, and their feedback used to validate the PW idea relative to sustainable design and construction. The results of data analysis showed that PW was better than conventional VE approach and thus, it was concluded that its inclusion in the VE job plan would benefit project owners by providing better value or improved project outcomes.

Keywords: construction project, function analysis, performance worth, sustainable construction, value engineering.

1. Introduction

Value engineering (VE) originated from General Electric, a defence contractor, as a strategic tool used by multidisciplinary team of professionals focusing on functions to deliver projects or systems at the lowest cost (Wao, 2015). L.D. Miles who initiated the VE idea at General Electric after World War II in the 1950s was faced with scarcity of resources and envisioned that items could only be bought for what they could do best or needed for. So the focus on function was key and a distinguishing factor in VE.

The Society of American Value Engineers (SAVE)-International Value Management Body of Knowledge (VMBOK) of 2019 and Wao (2015) defined VE as a systematic application of strategic techniques that identify function of systems where good teamwork, specific creativity approaches and good communication by multidisciplinary team of professionals are integrated to develop strategic systems that are aimed at meeting the project requirements at the lowest overall cost and highest performance and quality levels. Great team effort and understanding, high level of performance and optimal cost are vital goals in the VE process. Alternative systems must be carefully understood in terms of their functions or what they do best in a project before selecting those that are most preferred for the project. Selecting the needed alternative require creativity from VE team members and free flow of ideas without any form of hindrance. The VE team leader who steers the team has to ensure that the VE team focuses on greater level of analysis of systems while considering the functions and project requirements before incorporating suitable evaluation techniques to arrive at the most preferred alternatives. Using a method that is flawed or one that overemphasize some parameters such as performance, quality or cost may result in a decision that does not meet the project owner's overall requirements and possibly lead to project demise and owner dissatisfaction. VE employing appropriate method would ensure that the goals are met satisfactorily especially when focusing on better sustainable design and construction outcomes.

With sustainable construction, the goal is to meet the needs of the present population without threatening the ability of the future generation to meet their own needs in the built environment (Wao et al., 2016). This needs performance assessment of systems, ensuring that commissioning is well done, and that the performance level of systems is exceeding the goals over the life cycle of a project.

There are varied tools that can be used to assess the performance level of systems in projects but VE stands out to be a potential tool that can be used to develop desired systems that are geared towards better sustainability outcomes. However, close analysis of some of the conventional VE processes show limitations in the VE job plan, especially when the goal is to improve sustainability outcomes (Wao, 2014). Therefore, this research was centred on refocusing the conventional VE process to improve building sustainability outcomes especially the performance improvement of systems. The objective was to identify the possible limitation in the function identification and analysis phase of the VE methodology and then find possible ways to address it by developing a new VE method for performance improvement. The hypothesis was that the new approach would result in better building sustainability outcomes. The significance of the study was to provide project owners and construction industry professionals with a value-focused tool to improve performance of systems.

2. Literature Review

2.1. Value Engineering and Sustainable Construction

The success of a VE process depends on the success of the functions analysis of systems using Function Analysis System Technique (FAST) in addition to a multidisciplinary team of professionals who have good relationship and better communication amongst themselves. Function analysis helps in understanding the items by moving the team from a general understanding to specific inner detailing that could lead to improved end-value. Focusing on functions make the VE process unique and different from other problem solving techniques (SAVE International VMBOK, 2019, Wao et al., 2016). Specifically, function analysis identifies necessary functions and potentially unnecessary costs of a specific aspect of a project. Thus, it is important to spend a lot of time on function analysis using FAST. This is because the most important function may not be visible and that an unsound choice from a range of options can lead to a different solution leading to high cost. Figure 1 shows FAST diagramming details.

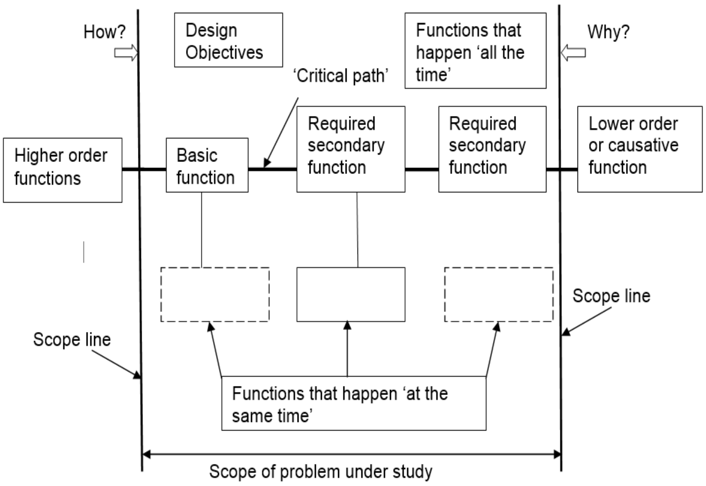

Figure 1. Technical FAST or function logic diagram (ASTM E2013-12).

The purpose in a project or system is in the higher order functions of FAST (Figure 1). Asking 'Why' determines the relationship between a higher order function and lower order function. The answer constitutes the higher order function. A logic check must be completed by asking 'How' the higher order function is realized. The answer must be the lower order function. The basic function is to the right of the left hand scope line and the secondary functions are to the right hand of the basic function and continue to the lower order function by asking 'How' questions (ASTM E2013-12; Wao, 2014). Overall, the main goal of function analysis is to develop a full understanding of the project systems. Once there is complete understanding of the functions, the project team members can then select areas for maximum return on the value study resources that are available for the project (Wao, 2014).

Both sustainable construction and VE can be used to ensure better performance and quality of project over the life cycle (Mahadik, 2015). To achieve this, sustainability principles are integrated in projects to improve on their value, and VE can be used to achieve this value improvement goal by providing avenues to select better options for inclusion in sustainable construction projects (Wao et al., 2016).

Researchers have proposed integrating VE with sustainable construction principles so as to deliver projects with enhanced value where the main goal is to have sustainability principles and cost effective systems over the life cycle of project (Wao, 2018; Gunarathne et al., 2022). This is hoped to benefit project owners largely as it will provide them with better value for their money spent in projects while at the same time have tangible benefits in terms of socio-economic and environmental sustainability otherwise called triple bottom-line approach to sustainability (Wao et al. 2016; Senarathne et al., 2014).

Research has shown that limitations in time, lack of guidance on proper integration of sustainability principles, lack of knowledge of and awareness on sustainability and conflicting perceptions on sustainability are some of the barriers for integrating sustainability with VE (Gunarathne et al., 2022; Abidin and Pasquire, 2007). However, as stated by Yu et al. (2018), a systematic VE Job Plan can effectively guide the inclusion of sustainability principles during project life cycle. This job plan must not have limitations if it is to be effective. However, critical look at it shows some limitations.

2.2. Limitations of the Function Analysis Phase of the Value Engineering Job Plan

Since VE focuses on saving the overall cost, it is often found that project owners tend to focus on reducing first cost and so they may over-emphasize the cost reduction aspect, thereby downgrading other key objectives such as improving quality or performance attributes. Over-emphasis on cost comes from ASTM E1699-14 standard that discusses cost. The standard, also called the conventional VE tool, has sections and subsections that discuss the cost-worth (CW) process in VE. Section 7.3.2 of the ASTM E1699-14 describes the importance of relating function to cost and has improvement methods in the event of cost escalation. In addition, ASTM E2013-12 standard describes value using cost reduction approach. Therefore, it is evident that sustainability or performance goals may be overlooked during VE study as attention is on the cost of systems rather than on performance or quality improvements (Wao, 2016). Thus, systems options for evaluation during the VE process are selected based on cost-to-worth ratios and not performance-to-worth basis. This could introduce bias in the end.

2.3. Alleviating the Limitation in the Function Identification and Analysis Phase of the VE Job Plan

Looking at the conventional VE process, the CW approach is first-cost driven. CW ratio identifies the systems that may need improvement by considering their CW ratios. Meeting the sustainability goals require refocusing the conventional VE process since there is a tendency to over-emphasize cost reduction at the expense of performance/quality improvement. Since, the CW analysis is conducted in the function analysis phase, improving the performance or quality outcome will be achieved by improving the guiding standard. This can be seen in ASTM E2013-12 standard which states that the FAST data help in identifying system's alternatives with respect to their function costs.

ASTM E1699-14 subsection 7.3.2.5 defines worth as the VE team's estimation of the least costs, and this is the initial or first cost which is presented in the cost estimate needed to perform a specific system function. Subsection 7.3.2.6 stipulates that the CW ratio is calculated by dividing the design professional's cost for each system or functional group by the basic worth (the VE team's cost estimation). If the resulting ratio is greater than 1:1 (cost is higher in the estimate than the VE team's estimate), then there is potential opportunity for cost improvement. This means that greater ratio implies greater chance for improvement using first-cost approach.

Worth can also mean the VE team's best or highest estimation of quality or performance as defined by the selected quality and performance indicators for the project system. The performance-worth (PW) maybe calculated by dividing the projected performance indicators by the VE team's target worth as represented by quality and performance indicators. Ratio less than 1:1, i.e., less performance realized from the design than the VE team's estimate implies a potential opportunity for improvement.

Integrating these changes in the VE job plan will consider all the VE objectives (cost, performance and quality improvements) in project. The VE team will discuss PW in addition to CW. The project owner can therefore obtain the best value for the lowest economic investment over the life cycle of a project.

3. Research Methods

The aim of this research was to refocus the conventional VE process to improve project sustainability outcomes. The objectives were to 1) identify limitation in the function analysis phase and find ways to alleviate the limitation, 2) evaluate the impact of the new VE method to sustainability. The hypothesis was that the new method would result in better building sustainability outcomes. The significance of the study was to provide owners and construction industry practitioners with a value-focused tool to improve performance of systems. Industry personnel were used in assessing the VE methods.

3.1. VE Practitioners and Survey Questionnaire

In order to provide a conclusive validation of the new or alternative VE approach, a group of VE practitioners (N = 15) were purposely selected to take part in this research requiring them to offer their opinions about the alternative VE approach aimed at improving sustainability outcomes. They were certified in value engineering (certified value specialists also called CVS) and were experienced in conducting VE in projects. A presentation was given showcasing the change in the conventional VE.

Prior to presenting to them, their consent to participate in the research through this presentation and subsequent survey was sought through the assistance of the Institution Review Board (IRB) which approved the presentation and the survey protocol. The presentation was then provided to the VE practitioners and it detailed out the limitations of the conventional VE method and the avenues that were proposed to counter the limitations relative to improving sustainable design and construction outcomes. They were given time to discuss it through questions and comment section of the presentation. Immediately after the presentation, the VE practitioners were sent the online survey questionnaire via Qualtrics software so as to gather their opinions about the limitations of conventional VE method and the proposed new approach to VE. The survey questionnaire entailed collection of the VE practitioners' demographic data such as number of years in construction industry, number of years involved with VE and sustainability assessment tool. Emphasis was placed on the VE specific questions as shown in Table 1.

Table 1. Survey questions specific to VE and sustainable or green construction outcome

Number	Type of question	Coding
Q.9	Whether or not to accept the various limitations in conventional VE process.	Yes = 1, No = 0
Q.10	Degree of agreement with the various limitations in conventional VE process in negatively impacting green building outcomes.	Strongly disagree = 1, Disagree = 2, Neither agree or Disagree = 3, Agree = 4, and Strongly agree = 5
Q.11	Level of satisfaction with the VE methods in meeting or improving building sustainability outcomes.	Very dissatisfied = 1, Dissatisfied = 2, Somewhat dissatisfied = 3, Neutral = 4, Somewhat satisfied = 5, Satisfied = 6, and Very satisfied = 7
Q.12	Additional thoughts or comments on VE and green building.	NA

4. Results and Discussion

The data from the survey of VE practitioners were analysed. The data were both quantitative and qualitative types (mixed method). Data analysis using SAS studio (2023) was mainly focused on the limitations of the conventional VE and the ability of the VE method to improve sustainability outcomes. The descriptive statistics results of the conventional VE and alternative VE were presented. The statistics mostly reported percentage scores and mean measures as part of the descriptive statistics because this was believed to provide good presentation of the data in a simplified format.

Those who completed the survey were Certified Value Specialists (CVS), university professors, directors and presidents of companies, construction managers, and civil engineers from all over the globe.

About 72% of the respondents had over 20 years of experience working in construction industry while 14% of them were 6-10 years and 11-15 years of experience respectively. For their experiences, 100% of them had used VE in their projects while 57% had used LEED or other green building rating systems. Of those who had used VE in their projects, about 72% of them were over 20 years of experience working with VE while 14% of them had 11-15 years and 16-20 years of experience respectively. For those who had worked with green building assessment tools like LEED, approximately 50% of them had 6-10 years of experience working with it while 25% had 2-5 years and 16-20 years respectively in working with it. This, in overall, depicted the high level of engagement in the construction industry and many years of using VE in projects which would imply greater reliability in the data or information they would provide because the many years meant experience and knowledge in their respective fields.

The respondents were also asked about the description of their respective construction companies. A complete 100% of the respondents reported that their companies specialized in VE while construction management and cost engineering areas of specialization accounted for 29% of the respondents respectively. About 14% were involved in general contracting while about 29% were in business management and risk management field. Their projects were mainly commercial (57%) and industrial (57%). Others were heavy civil (29%), manufacturing and mining (29%), and residential projects (14%). Their full engagement in VE means that the data were mostly in VE and would provide reliable interpretation for eventual accurate research generalizability.

They were also asked whether or not they accepted the limitations identified in the conventional VE process as actual or true limitations based on their VE experiences. Also, they were asked whether or not the identified limitations would negatively impact green building outcomes based on their opinions from the presentations and field experiences. Green buildings, sustainable buildings, energy efficient buildings, net zero energy buildings, high performance buildings and resource efficient projects were terms that were used interchangeably in the field of sustainable construction during the presentation.

Considering the responses to the limitations on whether or not they were true or actual limitations, more than half of the respondents (57.1%) believed that over-emphasis on cost was indeed a limitation. Considering the negative impact of the limitations to green building outcomes, about half of the respondents (42.9%) disagreed with the limitation pertaining to over-emphasis on cost while about 28.6% strongly agreed that it was actually a limitation relative to negatively impacting green building outcomes (Mean = 3.29). This feedback posed a potential venue for proposing a new method to VE whereby it was clearly feasible to discuss potential application of PW method to VE especially for performance improvement in sustainable construction projects.

The qualitative data also showed that value planning (VP) and value management (VM) were more encouraged as opposed to VE. Some respondents held that VE had for a long time been focused on reducing or cutting cost. Therefore, VP and VM would be preferred concepts to improve performance of systems using function analysis as the basis for value analysis (VA). The performance goal is where a respondent held that the biggest optimization in the VE process could be achieved through the use of performance based attributes weighted by the client prior to the start of the VE workshop. Function analysis stimulates creativity and would be easy to understand where teams use it in defining items rather than as an activity like in critical path method in project scheduling.

Some respondents held that VE, VM, and VA are terms used by many practitioners and are applied in different project stages. For example, VM is typically applied as early as possible in the project with the aim of optimizing costs, VE is applicable in all project stages and may be used for assessment of project alternatives or refinement of systems, while VA may be applied at design stages. Noteworthy is that they are all aimed at refining, reducing cost, and improving performance and quality of systems.

5. Conclusion

This research investigated the conventional VE method, identified some limitations in the function analysis VE phase and then proposed a potential approach that could be integrated in the VE methodology to improve its outcomes especially for sustainable projects where performance is always held in high regard. It determined and assessed the PW method in the function analysis phase of the VE job plan in comparison to the conventional VE method. VE practitioners were involved in the validation of VE PW approach whereby they were presented to and then provided their candid feedback through anonymous survey questionnaire. Analysis of the VE practitioners' feedback showed that the majority of them were in support of the PW idea, and that it could be a better approach in achieving sustainability goals in projects than conventional VE method. Thus, the hypothesis of the new VE approach being better and providing improved performance outcomes was supported. The PW idea could be a worthwhile inclusion in the VE function analysis phase to re-orient the VE teams, construction professionals, project owners and stakeholders from the routine thinking of cost reduction to inclusion of performance improvement ideas. The VE goals would be met while utilizing life cycle (and cost) analysis approach to attain the project goals. This research contributes to the VE studies body of knowledge especially those focusing on improving sustainable construction project outcomes.

Future research may delve into applying the new VE method in a case study building to investigate its overall impact in providing value to project owners. The greater value may show in 'platinum' certification in LEED or earning the 'restorative' achievement level in Envision for sustainable infrastructure projects.

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References

[1] N. Z. Abidin and C. L. Pasquire, "Revolutionize value management: A mode towards sustainability," International Journal of Project Management, vol. 25, no. 3, pp. 275–282, Apr. 2007, doi: 10.1016/j.ijproman.2006.10.005.

[2] "Practice for Constructing FAST Diagrams and Performing Function Analysis During Value Analysis Study", doi: 10.1520/e2013-12.

[3] "Practice for Performing Value Engineering (VE)/Value Analysis (VA) of Projects, Products and Processes", doi: 10.1520/e1699-14.

[4] A. S. Gunarathne, N. Zainudeen, C. S. R. Perera, and B. A. K. S. Perera, "A framework of an integrated sustainability and value engineering concepts for construction projects," International Journal of Construction Management, vol. 22, no. 11, pp. 2178–2190, May 2020, doi: 10.1080/15623599.2020.1768624.

[5] Mahadik UA., "Value engineering for cost reduction and sustainability in construction projects", IOSR Journal of Mechenical and Civil Engineering, 2015, 1:95–97.

[6] SAVE International Value Management Body of Knowledge, SAVE International, 2019.

[7] Senarathne D, Karunasena G, and Rathnayake U, "Enhancing the value in construction via integration of sustainable construction to value planning", Proceedings of 3rd World Construction Symposium 2014: Sustainability and Development in Built Environment; June 20–22; Colombo. Sri Lanka: University of Moratuwa. p. 192–203.

[8] J. O. Wao, "Value engineering methodology to improve building sustainability outcomes", Dissertation Presented at the University of Florida, Gainesville, USA, 2014, accessed May 14, 2023 https://www.proquest.com/openview/f35077ab7e9fba7ee679074fbeead0df/1?pq-origsite=gscholar&cbl=18750

[9] J. O. Wao, "A review of the value engineering methodology: Limitations and solutions for sustainable construction", In *55th* SAVE International Annual Conference: SAVE Value Summit, 2015, (pp. 7-9).

[10] J.O. Wao, Ries R, Flood I, and Kibert C, "Refocusing value engineering for sustainable construction", In 52nd ASC Annual International Conference Proceedings, 2016 (pp. 13-16).

[11] J. O. Wao, "Improving Creativity in the Value Engineering Process for Green Building Construction," Construction Research Congress 2018, Mar. 2018, doi: 10.1061/9780784481301.077.

[12] A. T. W. Yu, A. A. Javed, T. I. Lam, G. Q. Shen, and M. Sun, "Integrating value management into sustainable construction projects in Hong Kong," Engineering, Construction and Architectural Management, vol. 25, no. 11, pp. 1475–1500, Dec. 2018, doi: 10.1108/ecam-03-2017-0049.

A Framework for Crack Detection Based on Sensor Integration 3D Model for the Maintenance of Old Structures

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Abstract

The existing human-centered safety diagnosis method for structure maintenance has problems with time, cost, accuracy, and safety. Recently, many attempts have been made to quickly and accurately check the condition of structures for maintenance by utilizing equipment. In this research, a framework was established to derive the priority of repairing cracks based on a 3D model after data was obtained by combining LiDAR, high-resolution camera, and thermal imaging camera with drones. Drones serve as a moving object for obtaining data and can be used in places where it is difficult to access with manpower, thereby improving the safety of workers. The framework is as follows: Step 1 is obtaining data of a structure through each sensor, which is classified according to two purposes. In Step 1-1, Point Cloud Data is obtained through LiDAR, and crack images of the structure are obtained through high-resolutions camera. In this step, data can be obtained to determine the accurate location and size of cracks in the structure. In Step 1-2, thermal imaging data for measuring the depth of cracks is obtained through thermal imaging camera. Step 2 is processing and integrating data obtained through each sensor for 3D visualization of cracks on the structure. The PCD obtained through LiDAR is made into a mesh after removing noise, and a 3D model is constructed through texturing using high-resolution images and thermal images on the mesh, respectively. Step 3 is deriving the repair priority of cracks identified on the 3D model. Each crack has different characteristics such as location, size, and depth. For crack repair, cracks are classified according to grade and the repair priority is determined by considering the characteristics of crack. The framework can contribute to improving the economic efficiency, accuracy, and safety of structure maintenance by presenting criteria for deriving crack repair priorities.

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Keywords: multi-data integration, 3D model, reverse engineering, crack detection, maintenance

1. Introduction

Recently, the importance of maintenance has been emphasized due to the expansion, complexation, and rapid aging of construction projects. Old structures have weak durability, making them susceptible to problems such as leakage, cracking, and infiltration of weathering factors, which can lead to corrosion of reinforcing bars, concrete spalling, delamination, and reduced durability. To ensure the continuous safety management of structures, more advanced and continuous maintenance technologies are necessary [1]. However, current maintenance is labor-intensive and costly, and the visual inspection method of workers can vary depending on their skill and experience, which highlights the need for an objective safety inspection method [2]. In the construction industry, various attempts are being made to utilize drones for efficient and economical maintenance of old structures [3]. Previous studies on structural inspection technology using drones include Han. (2021), who conducted proximity photography and thermal imaging inspections of large structures that are difficult to access and visually inspect using human labor [4]. Kim et al. (2021) generated an orthographic image of dam facilities using drone photogrammetry technology and examined the validity of the technology [5]. Shin et al. (2022) developed a 3D structural analysis model by acquiring data from inside and outside of old structures using images captured by drones and ground-based LiDAR scanners to create 3D structural drawings

[6]. Many studies use drones equipped with sensors such as cameras and LiDAR to acquire structural data and utilize 3D modeling for maintenance. In this study, we equipped drones with LiDAR, high-resolution cameras, and thermal imaging cameras to acquire data, and developed a framework for prioritizing crack repairs based on 3D models after processing and integrating. Each sensor used in this study has its own advantages. LiDAR is useful for efficient acquisition of vast 3D data in wide areas, while high-resolution cameras can identify weathering states such as cracks from captured images. Thermal imaging cameras can also identify cracks and are effective in achieving more accurate results when used in combination with observations from regular images.

2. Methods

2.1. Instruments

The equipment used for data acquisition for 3D modeling in this study was as follows: a Matrice 300 RTK drone(Figure 2a) was used in Step 1, which is a quadcopter weighing 6.3 kg with a payload of 2.7 kg and a maximum flight time of 55 minutes, and has a manufacturer-declared range of 8 km. The Zenmuse L1 LiDAR(Figure 2b) was used, which has an accuracy of 0.1 m per 50 m in the horizontal plane and 0.05 m in the vertical direction. It has a maximum range of 190 m at a surface reflectivity of 10% and a measurement speed of 240,000 points/second [7]. In Step 1-2, the Zenmuse P1 camera(Figure 2c) was mounted on the drone, equipped with a DL 35 mm F2.8 LS ASPH lens with a resolution of 8192 × 5460 pixels (45 Mpix). In Step 2, the Matrice 30T drone(Figure 2d) was used to acquire data using the mounted thermal camera.

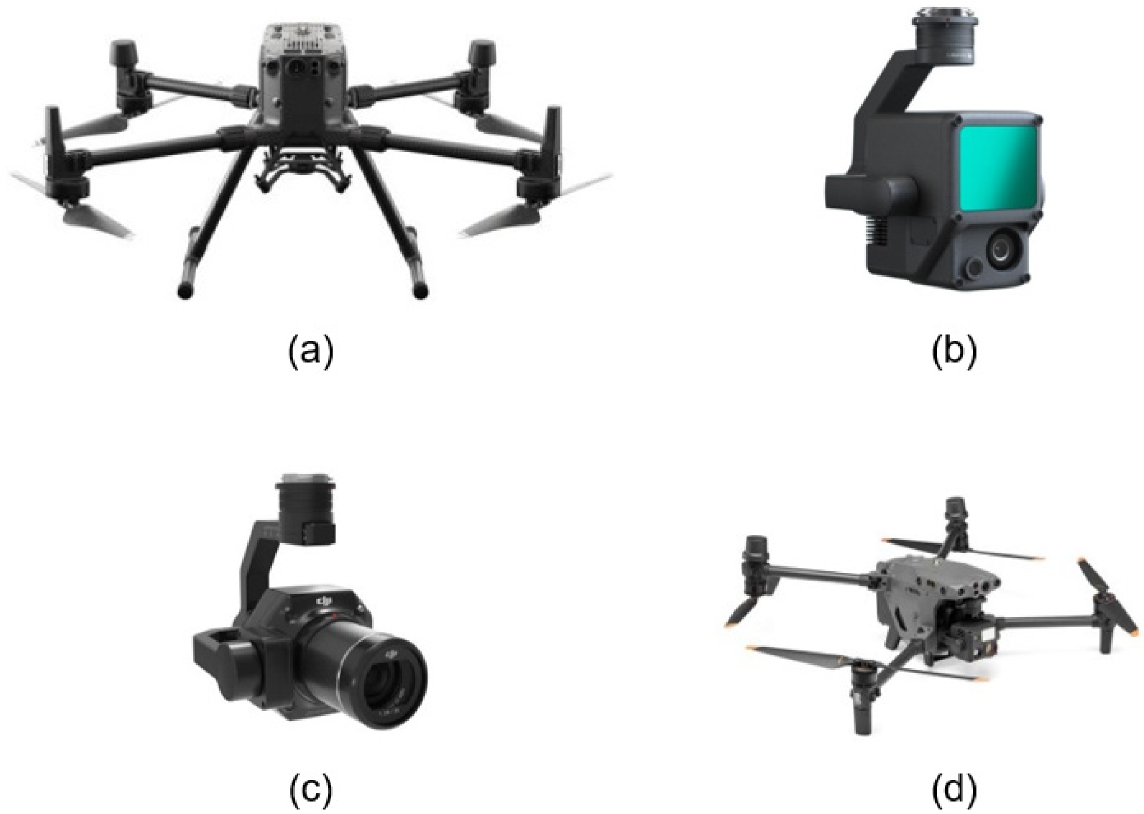


Fig. 2. (a) Matrice 300 RTK; (b) Zenmuse L1; (c) Zenmuse P1; (d) Matrice 30T

2.2. Research framework

The framework built in this study is shown in Figure 1. Step 1 is divided into two detailed steps according to the purpose to collect structure data using each sensor. In Step 1-1, Point Cloud Data is acquired through LiDAR and a crack image of the structure is obtained using a high-resolution camera. Through this process, data can be acquired to determine the exact location and size of cracks in the structure. In Step 1-2, thermal image (temperature) data is acquired to measure the crack depth using a thermal imaging camera. Step 2 is to visualize the cracks in the structure in 3D by processing and integrating the data acquired by each sensor. The PCD obtained through LiDAR is made into a mesh after removing noise, and a 3D model is built through texturing using high-resolution images and thermal images. Step 3 is the step of deriving the priority of crack repair confirmed through the built 3D model.

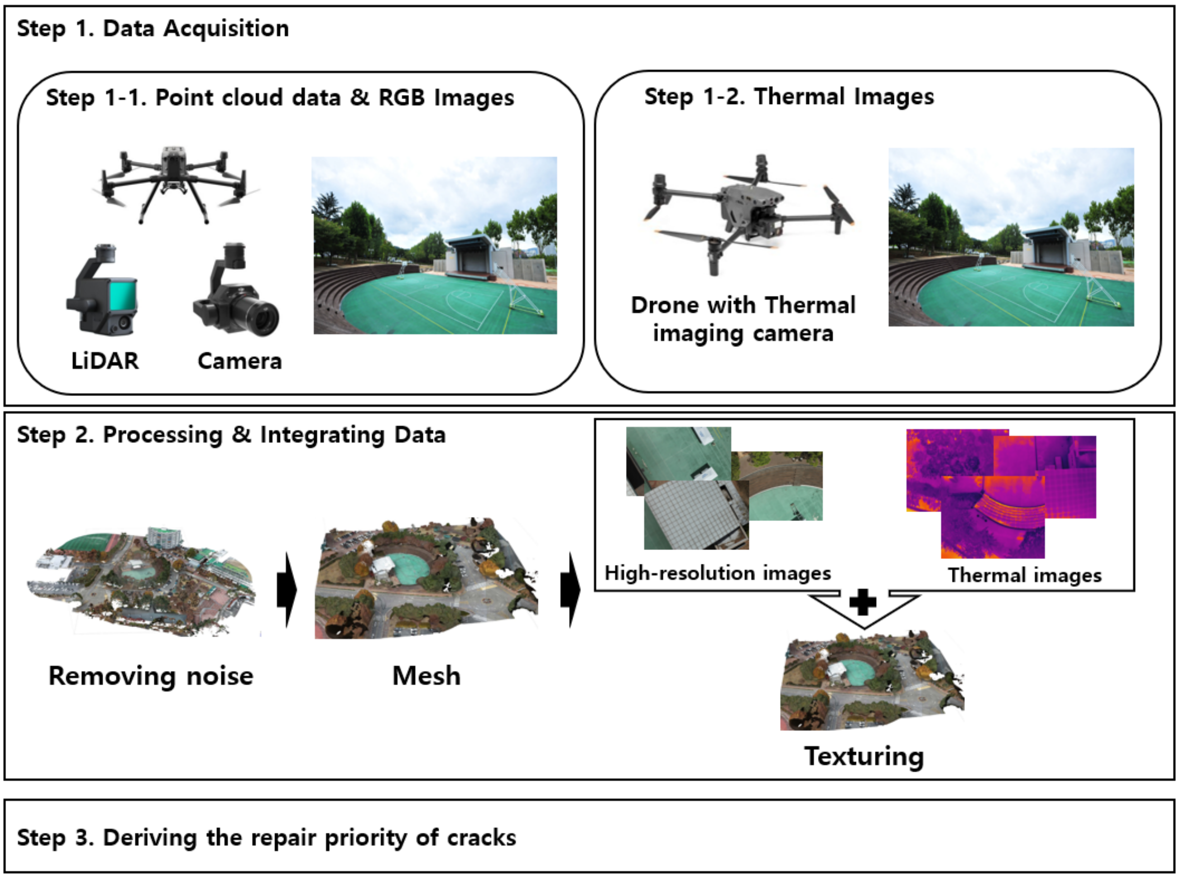


Fig. 1. Research Framework.

2.2.1. Step 1.

In the framework of Step 1, the target site is scanned using the Matrice 300 RTK with Zenmuse L1 LiDAR and high-resolution camera, Zenmuse P1. Firstly, in Step 1-1, the target site is scanned using Zenmuse L1 LiDAR to acquire point cloud data (PCD). In this study, a part of Chosun University located in Gwangju, South Korea was selected as the target site for scanning. The flight for PCD acquisition was conducted at an altitude of 30m, a speed of 3.8m/s, and with a 70% overlap, taking approximately 11 minutes to cover an area of about 6,200m^2. The high-resolution image acquisition was conducted using the Zenmuse P1 camera. The flight parameters were set to the same altitude and speed as for PCD acquisition, with both vertical and horizonal overlap set to 80%, taking approximately 9 minutes to scan the same target site. In Step 1-2, the target site was scanned using the thermal camera mounted on the Matrice 30T. The flight was conducted at an altitude of 30m, a speed of 2m/s, with a vertical and horizonal overlap of 90%, taking about 40 minutes to acquire thermal images. Table 1 shows the flight settings and duration for each equipment used in Step 1-1 and 1-2.

Table 1. An example

Step	Payload	Altitude(m)	Speed(m/s)	Time(min)	Overlap
1-1	Zenmuse L1	30	3.8	11	70
	Zenmuse P1	30	3.8	9	80
1-2	Matrice 30T	30	2	40	90

2.2.2. Step 2.

Step 2 involves processing and integrating data acquired from each sensor to visualize 3D cracks in structures. For data processing and integrating, Pix 4D Survey and DJI Terra software were used in this study. First, the point cloud data (PCD) acquired through LiDAR is processed to remove noise and create a mesh. This step visualizes the 3D position information for maintaining structures. The created mesh is then used to build a 3D model using texture work with high-resolution images and thermal images. Texture work is performed on the mesh using high-resolution images and thermal images acquired from LiDAR to confirm the accurate 3D coordinate of the cracks.

2.2.3. Step 3.

Step 3 is a process of determining the priority of repairing cracks based on the 3D model built in Step 2. Each crack has different characteristics such as location, size, and depth. To repair the cracks, they are classified into different grades based on their characteristics, and the priority of repair is determined.

3. Results

3.1. Step 1.

In Step 1, we acquired data using drones, LiDAR, high-resolution cameras, and thermal cameras through three flights. During a total flight time of about one hour, we acquired 121,443,499 points through LiDAR (Figure 2), 528 images with a resolution of 8192 × 5460 through high-resolution cameras (Figure 3), and 914 images with a resolution of 1280 × 1024 through thermal cameras due to relatively high overlap (Figure 4) for analysis.

Fig. 2. Raw data_121,443,499 points.

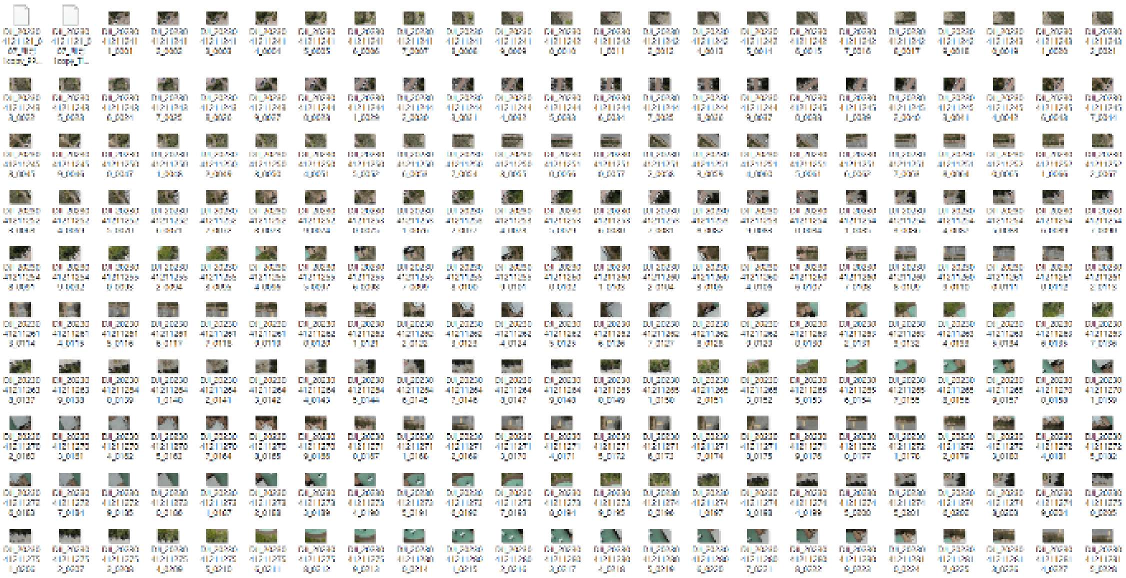


Fig. 3. Raw data_528 high-resolution images

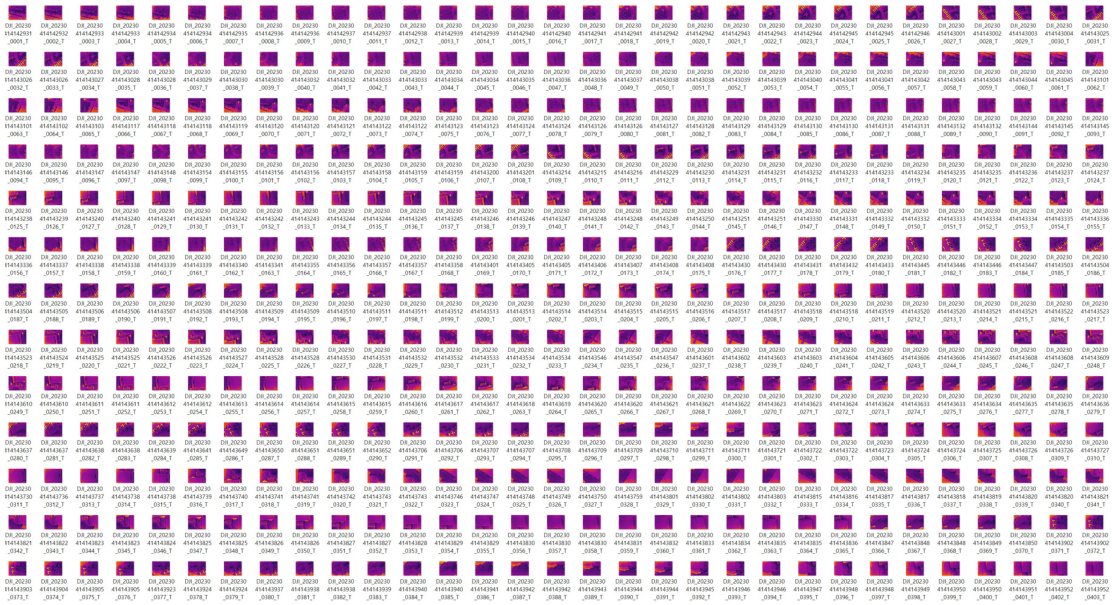
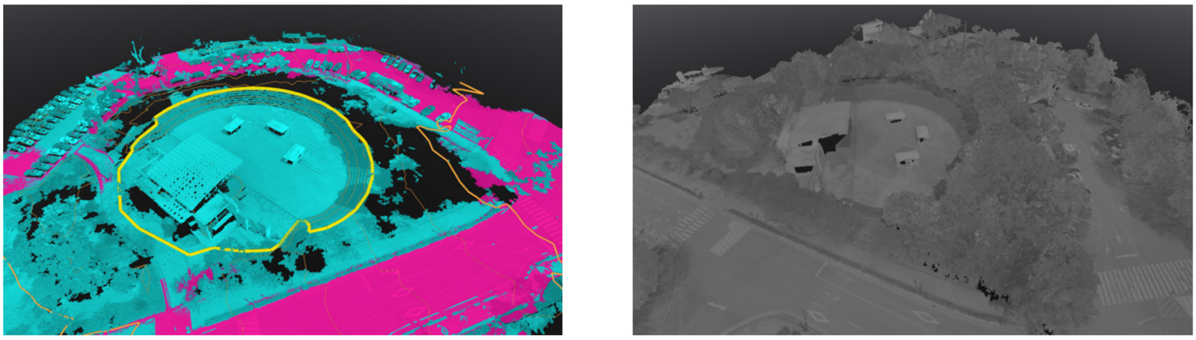


Fig. 4. Raw data_914 thermal images

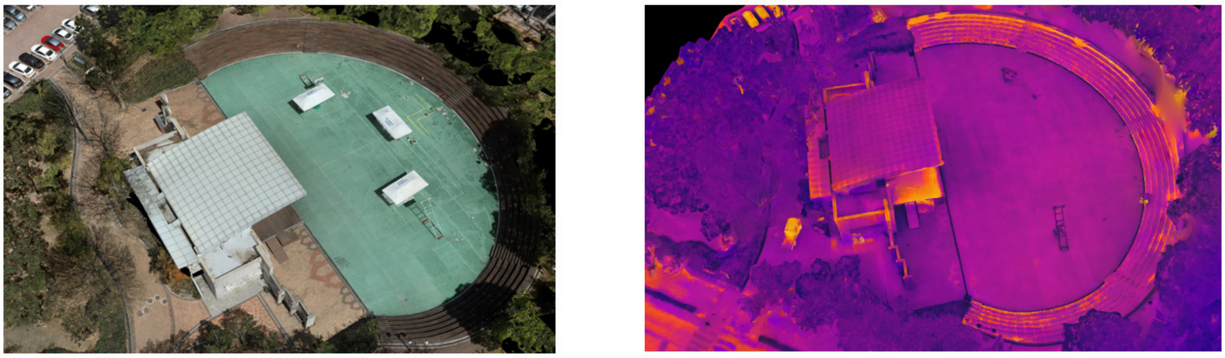
3.2. Step 2.

In Step 2, Pix 4D Survey and DJI Terra software were used to process and integrate the raw data acquired from the instruments. Firstly, the noise and outliers in the LiDAR point cloud data were removed (Figure 4a). This is a crucial step to ensure the quality of the 3D model and to reduce analysis time. Next, point clouds were extracted from the high-resolution and thermal images for integrating with the LiDAR data. The Pix 4D software used in this study found feature points and correspondences between images to calculate the location, direction, and elevation of the camera and generate point cloud data in 3D format. The extracted point clouds were integrated and made into mesh(Figure 4b), and then each image was texturized to build the 3D model. Figure 5 shows the final 3D model textured with the high-resolution image (Figure 5a) and thermal image (Figure 5b).



(a) (b)

Fig. 4. (a) Removing noise & outlier; (b) Mesh



(a) (b)

Fig. 5. (a) Model textured with high-resolution images; (b) Model textured with thermal images

3.3. Step 3.

In Step 3, cracks in a structure are classified and prioritized for repair based on their location, size, and depth, as this approach is more cost-effective. This step involves examining the location, size, and depth of cracks in the constructed 3D model to determine the priority of repair, which enables data-driven and efficient repair work. In the 3D model built in this study, the 3D coordinates of each point and the length and volume of the particular points can be checked.

4. Conclusion

Resently, human-based safety inspection methods have issues with time, cost, accuracy, and safety. To address this, this study proposes a sensor-integrated 3D model-based crack detection framework for maintaining old structures. The framework consists of three main steps. In Step 1, data is acquired using a drone equipped with LiDAR, high-resolution camera, and thermal camera. In Step 2, the data acquired from each sensor is processed and integrated to visualize a 3D model. In Step 3, the priority for repairing identified cracks is determined from the constructed 3D model. Using this framework, a 3D model of the structure for crack maintenance was built. The accurate 3D coordinates, size, and other characteristics of the cracks in the structure can be quantitatively confirmed and managed, improving accuracy. In addition, the thermal images can be used to detect structural damage that is difficult to identify with the naked eye. Moreover, the data acquisition process is safe and can be completed within a short time of about an hour, compared to the conventional inspection method. This study has limitations in that only commercial software was used to perform 3D modeling, despite the wide range of algorithms available for post-processing in 3D modeling. Future research will address these limitations through: 1) evaluating the applicability of various data preprocessing algorithms for improving 3D model refinement, 2) verifying the accuracy of crack classification in structures, and 3) performing advanced analysis to determine priorities for crack repair.

Acknowledgements

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References

[1] "Development of Rapid and Precise Repair/Reinforcement Technology for Smart Maintenance of Infrastructure" https://www.dbpia.co.kr/pdf/pdfView.do?nodeId=NODE11214034&googleIPSandBox=false&mark=0&ipRange=false&accessgl=Y&language=ko_KR&hasTopBanner=true (Access date: 04.15.2023)

[2] J. W Kim, Y. W Jung, and H. C Rhim, "Study on Structure Visual Inspection Technology using Drones and Image Analysis Techniques", Journal of the Korea Institute of Building Construction, pp. 545-557, 2017, doi: 10.5345/JKIBC.2017.17.6.545.

[3] Y. Li and C. Liu, "Applications of multirotor drone technologies in construction management", International Journal of Construction Management, pp. 401-412, 2018, doi: 10.1080/15623599.2018.1452101.

[4] D. Y Han, "Building Modeling Using Drone Thermal Images", Journal of The Korean Cadastre Information Association, pp. 3-10, 2021, doi: 10.46416/JKCIA.2021.12.23.

[5] T. H. Kim, J. H. Lee, D. S. Kim, and S. B. Lee, "A Study on Dam Exterior Inspection and Cost Standards using Drones", Journal of the Society of Disaster Information, pp. 608-616, 2021, doi: 10.15683/kosdi.2021.9.30.608.

[6] C. H. Shin, G. J. Min, G. G. Kim, P. Jeon, H. Park, and S. H. Cho, "A Study on the 3D Precise Modeling of Old Structures Using Merged Point Cloud from Drone Images and LiDAR Scanning Data", Explosives and Blasting, pp. 15-26, 2022, doi: 10.22704/ksee.2022.40.4.015.

[7] M. Štroner, R. Urban, T. Křemen and J. Braun, "UAV DTM acquisition in a forested area – comparison of low-cost photogrammetry (DJI Zenmuse P1) and LiDAR solutions (DJI Zenmuse L1)", European Journal of Remote Sensing, 2021, DOI: 10.1080/22797254.2023.2179942.

A DESCRIPTIVE DIGITAL TWIN TO SUPPORT FACILITY MAINTENANCE

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Abstract

A digital twin is a digital representation of a physical space, asset, or process. Digital twins are set up to include static (historical) record data and to capture dynamic real-time data from connected sensors, actuators, and other devices. Recent literature has shown that there is a need for more Digital Twin implementation research to explore ways to integrate available technologies in order to define and test alternative digital twin system architectures. This paper focuses on the development and implementation of a descriptive digital twin prototype for various mechanical equipment housed in a 3-story classroom and laboratory building on the campus of an academic institution. The prototype was developed to test its ability to assist facility staff in monitoring the operational performance data of some components of the mechanical system in the building. The digital twin system architecture utilizes Navisworks models representing the different mechanical components. iConstruct Genus and BLogic VCAD were used to process the model file for import into MS Power BI. Static data collected from design drawings and submittals were linked to the model in Power BI. Real-time performance data collected from sensors attached to different equipment in the building were linked to the model in Power BI through an excel interface. The digital twin implementation involved regular meetings with facility staff over a period of six months to understand how the performance data is captured and interpreted for diagnostics and to receive feedback on the design and layout of the digital twin dashboards. During some of the meetings, some facility staff members self-navigated through the prototype to provide input on usability. Feedback received highlighted benefits realized from integrating static and dynamic data in a central platform that links the data to the graphical model. This provided access to all types of information within a single platform allowing a better visualization of the information and faster response to address facility maintenance needs or emergency requests.

Keywords: building information model, digital twin, facility maintenance, internet of things, power bi.

1. Introduction

[1] defined digital twin for facility management to be a virtual representation of physical assets, space, or process where data from physical assets are collected and transferred to the virtual representation using sensors/edge devices. [2] provided a more project driven definition of Digital Twin by labeling Digital Twin as a dynamic data-supported framework that acts as an enabler leading to results, products, outcomes, or new technologies in a business. Digital Twin is a means to an end, where the end is defined as solving real-world problems using real-world data.

Digital Twins are capable of utilizing static asset data and real time operational data to support virtual inspection, analysis, and maintenance of assets. Project stakeholders such as facility managers can utilize Digital Twins to ensure that the data related to the building lifecycle are maintained, verified, validated, and analyzed through the building lifecycle [1].

Depending on how different types of data are linked, processed, and utilized by Digital Twins, leading industry organizations and the global research community have provided various classifications to define different maturity levels of a Digital Twin and its expected capabilities at each level. Table 1 shows an example of one classification provided [1]:

Table 1. Example Levels of Maturity Classification of a Digital Twin

Digital Twin Level of Maturity	Capability	Ability – Functionality (What it Does)
Descriptive (What happened?)	Data Visualization (Data Display)	Use visualization tools to display static (historical) record data and dynamic real-time data (representing the current status of the physical twin) to present issues that may require attention or actions or may need to be resolved.
Informative (Why did it happen?)	Data Analysis	Leverage data analysis tools to generate insights that explain the issues identified and the reasons why they have occurred.
Predictive (What will happen then?)	Prediction of Future Events	Leverage intelligent predictive tools (e.g. machine learning) to forecast the behavior and future state of the physical twin (i.e. what may happen to the physical entity) based on reasons identified from issues detected.
Prescriptive (What should be done?)	Prescription of Solutions and Actions	Leverage prescriptive tools (e.g. machine learning) to suggest solutions and propose interventions to resolve the issues before they result in bigger problems.
Autonomous (Self-tune and self-heal)	Intelligence	Implement AI techniques including ML, natural language processing, knowledge modeling and representation, reasoning, inferencing, etc. to perform actions and take decisions like humans, to autonomously identify issues, determine reasons and resolve problems.

Linking dynamic real-time operational data of an asset to its 3D model provides advantages to the utilization of the 3D model beyond established capabilities of the current state of the art of BIM. These advantages could include report on the location and functional or operational status of the asset. Facility managers can utilize Digital Twin to monitor asset performance in real time allowing them to make informed decisions about asset maintenance and management. Linking of real time data in a Digital Twin also enables prognostic and diagnostic opportunities in facility management [1]. To accelerate the implementation and adoption of Digital Twin in the AEC/FM industry, more research needs to be conducted focused on digital twin implementation [3].

[4] created a digital twin by using IoT camera-based sensors to monitor occupancy in buildings. A framework for smart asset management using digital twins was developed by [5]. Research was also conducted to support urban facility management using digital twin where [6] presented design building blocks of the digital twin. Use of analytical ability of the digital twin to find anomalies in asset performance and support its management has been proposed by [7]. Facility management of a healthcare facility has also been explored by [8].

This paper focuses on describing the development of a descriptive digital twin for various mechanical equipment in a 3-story academic building using a case study approach. The digital twin uses Power BI as the central platform to integrate both static (historical) record data and dynamic real-time sensor data with a graphical model of the mechanical system. Four main dashboards were created to display the data using a bi-directional interaction with the graphical elements of the model. The visualization of static and dynamic data allows to provide a descriptive digital representation of the critical equipment of the mechanical system. Visualization of dynamic data for each equipment allows to depict the current status of the physical twin and identify any issues that require the attention of facility staff that may need further actions to resolve the issues.

The next section provides an overview of the case study used in the research. Section 3 details the methodology and its implementation adopted by the authors in this paper. Followed by section 4 detailing the conclusion and discussion of the findings of this paper.

2. Case Study Overview

The digital twin implementation focused on the mechanical system for a 3-story classroom and laboratory building on the campus of a large academic institution. Fig. 1 shows the Navisworks model for the building provided by the facility staff. The model was configured to show the main building in transparent mode and highlight the mechanical room and the three air handling units, AHU-1A/1B used in the digital twin implementation, and AHU-2. The mechanical room is located on the ground floor and includes various equipment such as the chilled water and hot water pumps, heat exchangers, expansion tanks and steam pressure reducing valves. The air handling units are located on the roof and provide the primary heating, cooling, and ventilation for the building. The AHUs utilize chilled water and lowpressure steam produced by the university central utility plant.

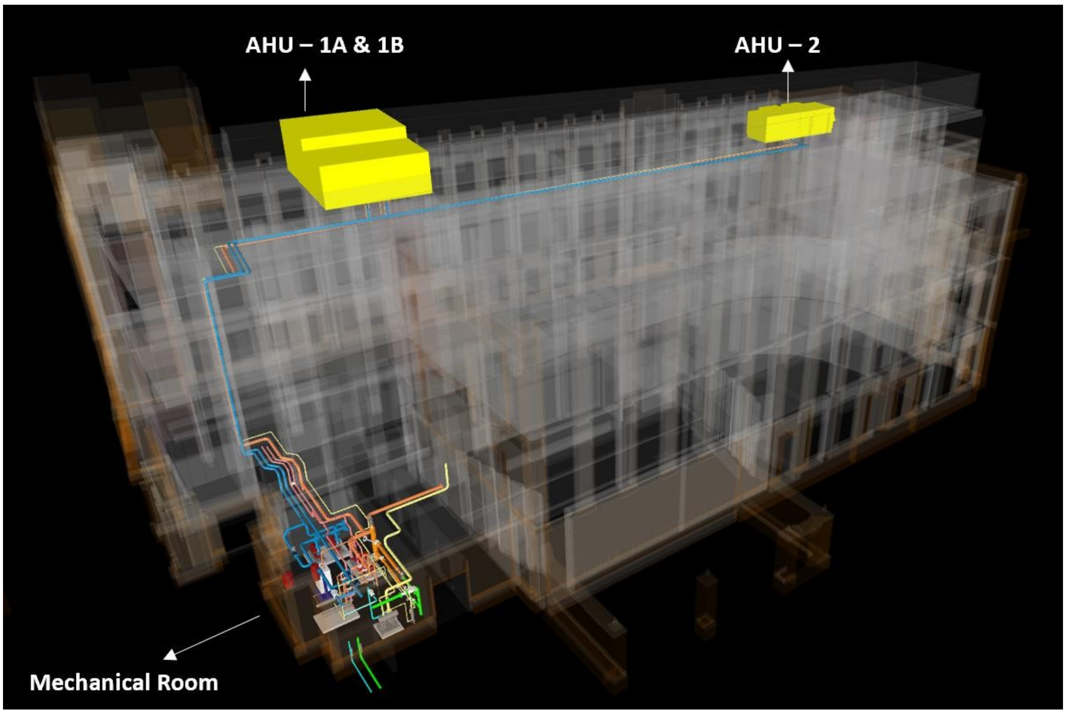

Fig. 1. Academic building showing mechanical room and AHUs.

The Navisworks model file provided by the facility staff had to be slightly modified to add graphical elements used in the digital twin development. AHU-1A & 1B were originally modelled as a single box. This box was replaced by two individual boxes to represent each individual unit and allow to attach static data to each unit separately. In the mechanical room, most of the valves were not modelled and had to be graphically added to the model to allow to track the valve opening positions (status) as part of the dynamic data captured and linked in the Power BI central platform. This included chilled water differential pressure (DP) valve, Chilled water bypass valve, Steam (STM) heat exchanger (HX1) 1/3 valve, and so on. Water meters were also added to represent data such as water usage, water flow, etc. Various sensor probes were added to represent sensors measuring pressure and temperature of water and steam.

A separate detailed model for the two main air handling units used for the digital twin implementation was created by the authors. Fig. 2 shows the Revit model for AHU-1A and AHU-1B illustrating its detailed components including outside supply and return air plenums, fans, valves, and energy recovery wheels. Sensors measuring dynamic data in specified location were also modelled.

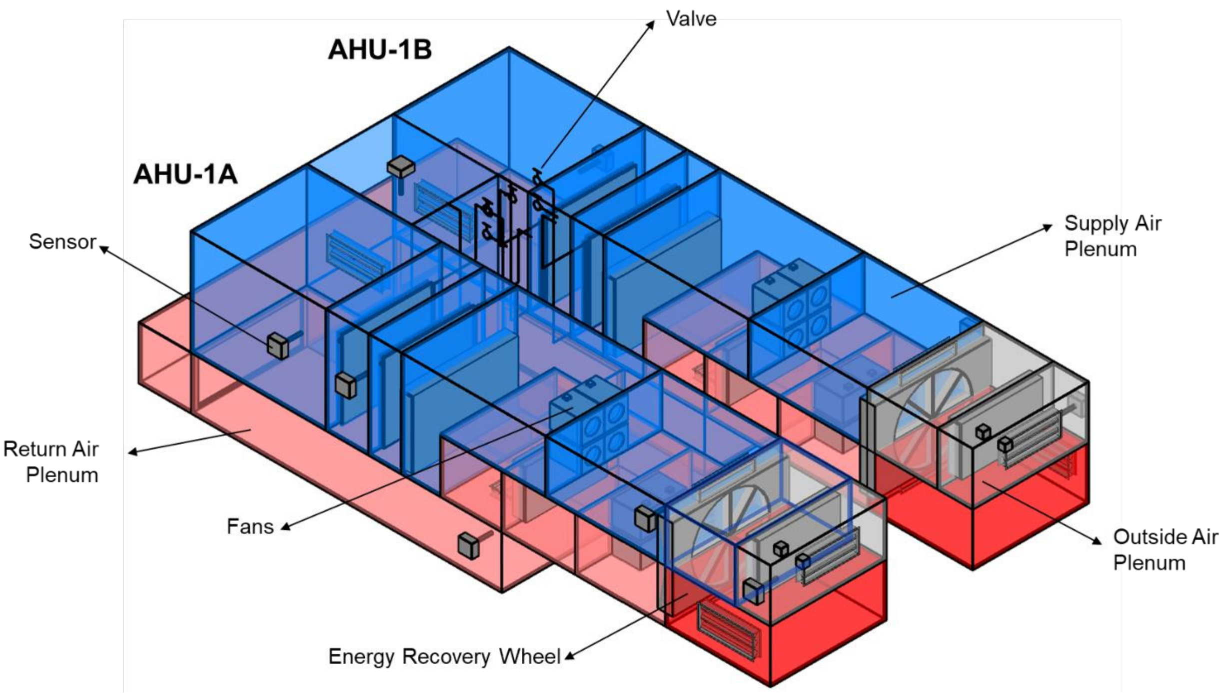

Fig. 2. Developed detailed 3D model of AHU – 1A & 1B.

Static data representing historical record information (e.g. model number, serial number, warranty dates, etc.) were captured from 2D plans and submittals and stored using an Excel format. The data was later input in the Power BI digital twin central platform and linked to the model. Static data could have been input directly to the graphical elements in Navisworks. The research team chose to link the data to the model in Power BI for more flexibility in case editing or reformatting of the data was required. Dynamic data from various sensors installed to track performance and operational data of equipment for regular maintenance purposes was also input and linked to the model in Power BI. Data from sensors is collected by a central BAS (Building Automation System) installed in the building and transmitted to a cloud-based SQL server. Required dynamic data was provided weekly to the research team in an Excel format. Accessing the data directly from the SQL server was not possible due to security reasons.

3. Methodology

The two main components of the descriptive digital twin are the 3D graphical model and static and dynamic equipment data. During the period of the project that lasted over 6 months, the authors had regular weekly or bi-weekly meetings with the facility staff to discuss what equipment to include in the development, determine what sensor data to use and conduct reviews of the prototype and make modifications based on feedback received. Fig. 3 summarizes the steps to create the digital twin.

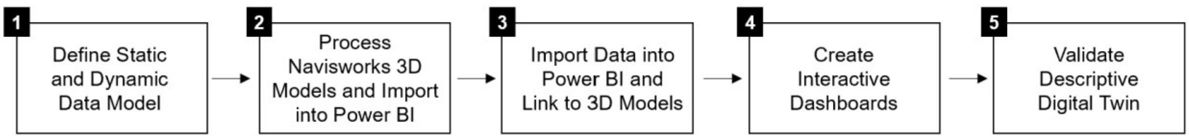

Fig. 3. Process to create the descriptive digital twin.

3.1. Define Data Model

Based on discussions with facility staff, four categories of mechanical systems were identified for inclusion in the digital twin prototype: chilled water system, hot water system, steam system, and forced air equipment (AHU-1A and AHU-1B). AHU-2 is a smaller unit with comparable data set to the other two bigger units and, therefore, was not included in the case study. Table 2 provides examples of static data for one of the air handling units. Fig. 4 shows example of dynamic data for the same equipment.

Table 2. Examples of Static data for AHU-1A.

Parameter	Value
ASSET_ID	AHU-1A
ASSET_DESCRIPTION	Air Handling Unit
WARR_DATE_TO	2021
TOTAL COOLING CAPACITY	1470.2 MBH

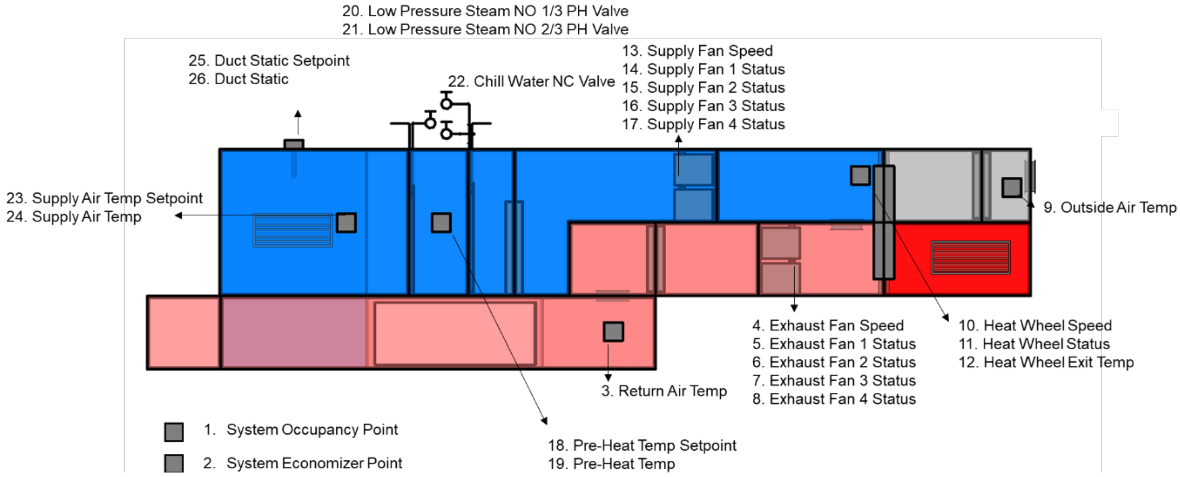

Fig. 4. Examples of dynamic data for AHU-1A.

3.2. Process 3D Navisworks Models and Import into Power BI

The final building and AHU Navisworks models shown previously in Fig.1 and Fig. 2 were uploaded into the BLogic VCAD platform to generate a Power BI template file. VCAD allows users to upload 3D models in Revit, Navisworks, or IFC file formats to generate a Power BI template file containing the visuals of 3D graphics and any built-in data. iConstruct Genus is a similar platform that were tested by the authors and allows to convert Navisworks files into a readable file format for Power BI also using the Autodesk Forge visual. The converted Navisworks file using the VCAD platform was ultimately the one used in this research because of its ability to provide bi-direction connectivity between the 3D model and any linked external data within the Power BI platform. Within Power BI, this bi-directional connectivity allowed to highlight model graphical elements when data points were selected, or highlight data in tables and visuals when model graphical elements were selected. Additionally, the VCAD generated Power BI template files were further modified inside Power BI to eliminate unnecessary visuals and dashboards. These are automatically generated by VCAD during the conversion process and included with the files when imported into Power BI. Fig. 5 provides a summary for this process.

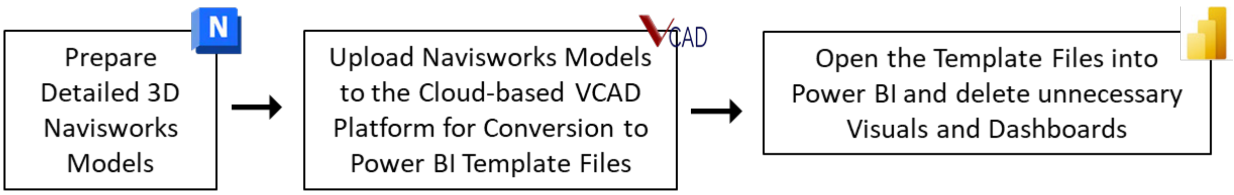

Fig.5. Process to generate the Power BI template files using VCAD.

3.3. Import Static and Dynamic Data into Power BI and Link to Graphical Elements of the Various Models

The static data collected from 2D plans and submittals was captured using an Excel spreadsheet. The respective element's GUIDs were also identified and extracted from the 3D model and entered into the spreadsheet. GUIDs and the static data were imported into the Power BI to be linked to the 3D model.

The dynamic data from the building BAS (Building Automation System) was provided to the research team weekly in Excel format. This data was cleaned to represent time stamp as rows and sensor IDs and their data in columns. The research team also created another table with the sensor IDs and corresponding GUIDs identified manually from the 3D model. Both tables were then imported into the Power BI and the dynamic data was linked to the 3D model using the GUIDs and sensor IDs table.

Once static and dynamic data were imported into the Power BI, the VCAD automatically generated tables of the model were linked to the imported data tables using common GUIDs. One of the VCAD model tables, "VCAD_Properties" contains a "Value" column with all the property values embedded in the 3D model including GUIDs. The static data table was linked to the 3D model table by creating a relationship between both tables. The relationship was established based on the GUIDs column in static data to the value column in "VCAD_Properties" table. To link the dynamic data tables to the 3D model, two relationships were created in Power BI. One relationship was created between the "VCAD_Properties" table and GUIDs and sensor IDs table using the GUIDs column in each table. The second relationship was between the GUIDs and sensor IDs table and the dynamic data tables using the sensor ID columns. These new relationships established the connections between the imported dynamic data and the 3D model.

3.4. Create Digital Twin Dashboards

Fig. 6. Dashboards created for the Descriptive Digital Twin.

As shown in Fig. 6, a total of 9 dashboards were created to display and visualize static and dynamic data linked to the graphical models. Dashboards 1 and 2 are intended to provide the user with a graphical interface to manipulate and navigate the mechanical room model and the AHU-1A and 1B models respectively. This allows users to become familiar with the detailed components in each model and their relative location to other components. Dashboards 3 and 4 provide various visuals that display static data for the mechanical room equipment. Dashboards 5, 6 and 7 provide various visuals that display dynamic data for the chilled water system, hot water system and low-pressure stem system respectively. All are located in the mechanical room. Similarly, dashboards 8 and 9 displays static and dynamic data for the forced air equipment (AHU-1a and AHU-1B).

As indicated earlier, graphical model elements in these dashboards are linked to the data in the visuals using a bi-directional relationship. If a data point in any of the visuals are selected, the corresponding model element linked to the data is highlighted and vice versa. Dashboards displaying static data were augmented with slicer visuals that allow users to search equipment by specific data parameters and automatically highlight elements in the model graphical window. Fig. 7 and Fig. 8 show enlarged images of dashboards 3 and 9 respectively as examples.

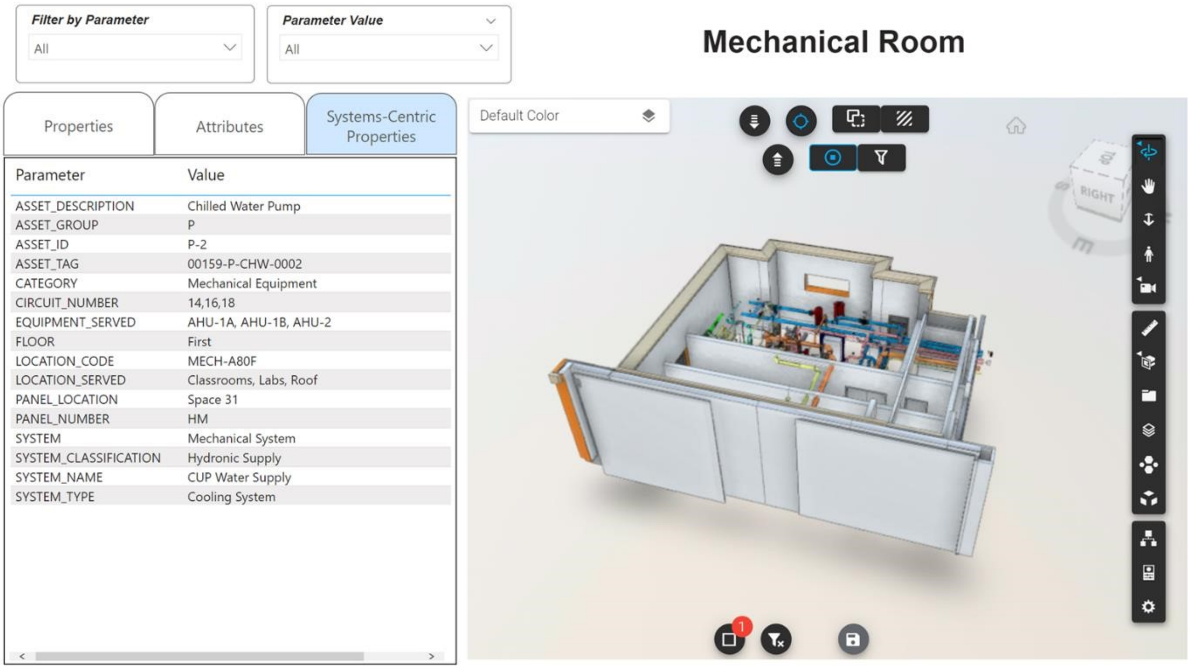

Fig. 7. Dashboard 3

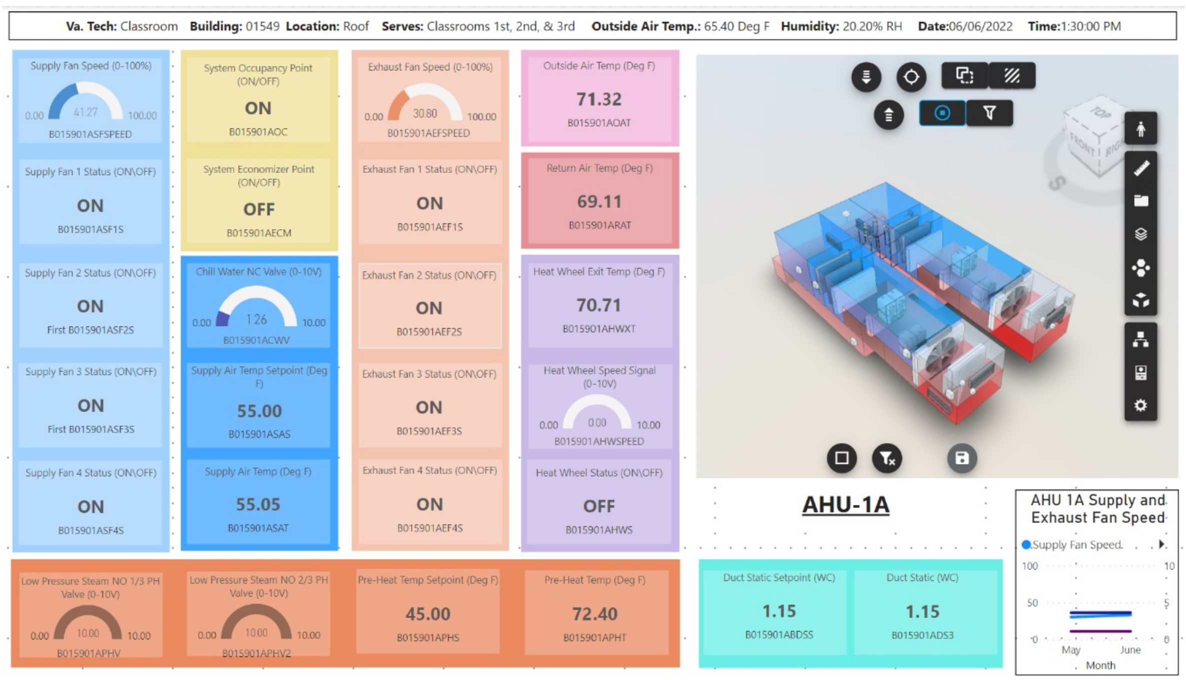

Fig. 8. Dashboard 9.

3.5. Validate the Descriptive Digital Twin

During the development and following the completion of the digital twin, the authors conducted six onehour interviews with facility staff to discuss the layout and design of the dashboards and receive feedback. The dashboards were continuously updated by grouping the visuals of related datapoints and arranging the grouped visuals in a particular order based on the preferences of the facility staff and how they perceived the order of organizing and accessing the data. Historical trend data graphs of important data points like supply and exhaust fans were also added to provide insights into the performance of those important assets. According to the facility staff, this helped them in identifying any abnormal performance of the assets that would allow to flag any maintenance issue or predict future failures.

Power BI also provides a cloud-based service option, where the created dashboards can be published and shared with other users within the organization or publicly. The developed Digital Twin dashboards were published from the Power BI Desktop to the Power BI Service to share with the facility staff as an end product.

4. Conclusion

The developed Descriptive Digital Twin allows to visualize the current status of the asset by providing the 3D graphics and its static and dynamic data. This digital twin allows the facility staff to navigate the 3D model and retrieve the data associated with any asset with ease. It also helps visualizing the asset's location and special arrangement beforehand to better diagnose its status, hence saving time during actual maintenance work. Without this digital twin, the facility staff has to review separately the 2D plans and BAS diagrams to visualize the data and establish relationships between equipment in the plans and data presented in BAS diagrams. This correlation of different systems can differ from person to person based on their understanding. It is also very time consuming which can be otherwise invested in diagnosing the issue.

The Descriptive Digital Twin can be upgraded to an Informative twin by performing analysis on the asset data to identify any patterns of problems. This can be further upgraded to a Predictive twin by implementing machine learning algorithms to predict what may happen based on the data analysis performed. As there is a gap in the implementation of digital twins, the authors agree with [3] that more implementation research of digital twins is essential to the AEC industry. The implementation research of digital twins not only provides validation of the methods, but also helps in the maturity and evolution of digital twins in various possible ways.

References

[1] A. Harode, W. Thabet, and P. Dongre, "A tool-based system architecture for a digital twin: a case study in a healthcare facility," *Journal of Information Technology in Construction (ITcon),* vol. 28, no. 6, pp. 107-137, 2023, doi: 10.36680/j.itcon.2023.006.

[2] "Digital twin: bring your data to life for better performance." Schneider Electric. https://www.se.com/ww/en/download/document/DT_eguide_09-10-19AR0_EN/ (accessed May 15, 2023).

[3] L. F. Durão, S. Haag, R. Anderl, K. Schützer, and E. Zancul, "Digital twin requirements in the context of industry 4.0," in *IFIP international conference on product lifecycle management*, 2018: Springer, pp. 204-214, doi: 10.1007/978-3030-01614-2_19.

[4] E. Seghezzi *et al.*, "Towards an occupancy-oriented digital twin for facility management: Test campaign and sensors assessment," *Applied Sciences,* vol. 11, no. 7, p. 3108, 2021, doi: 10.3390/app11073108.

[5] Q. Lu, X. Xie, J. Heaton, A. K. Parlikad, and J. Schooling, "From BIM towards digital twin: Strategy and future development for smart asset management," *Service Oriented, Holonic and Multi-agent Manufacturing Systems for Industry of the Future: Proceedings of SOHOMA 2019 9,* pp. 392-404, 2020, doi: 10.1007/978-3-030-27477-1_30.

[6] A. Bujari, A. Calvio, L. Foschini, A. Sabbioni, and A. Corradi, "IPPODAMO: A Digital Twin Support for Smart Cities Facility Management," in *Proceedings of the Conference on Information Technology for Social Good*, 2021, pp. 49-54, doi: 10.1145/3462203.3475919.

[7] X. Xie, Q. Lu, A. K. Parlikad, and J. M. Schooling, "Digital twin enabled asset anomaly detection for building facility management," *IFAC-PapersOnLine,* vol. 53, no. 3, pp. 380-385, 2020, doi: 10.1016/j.ifacol.2020.11.061.

[8] Y. Song and Y. Li, "Digital Twin Aided Healthcare Facility Management: A Case Study of Shanghai Tongji Hospital," in *Construction Research Congress 2022*, 2022, pp. 1145-1155, doi: 10.1061/9780784483961.120.

A PLELIMINARY STUDY ON AUTOMATIC INTERVAL MEASUREMENT MODEL FOR JACK SUPPORT

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Abstract

This study proposes a model to measure the installation spacing of jack supports, which play a role in supporting the structure load during construction. The proposed model consists of two parts; one part is the jack support segmentation in an image, and another part is the installation interval measurement. The results of this study contribute to ensuring the construction quality of jack supports and further preventing building collapse accidents. For the further research, we will research the automated camera calibration algorithm to gain the angle and height of the camera.

Keywords: camera calibration, instance segmentation, jack support, measurement.

1. Introduction

The jack support is widely used one of temporary structures used to prevent collapse accidents at construction and demolition stages [1]. Jack supports must be installed at appropriate intervals after checking the structural design drawing and jack support installation specifications. Compared to the specification, if jack supports are installed at too wide intervals, they cannot support the force, leading to a collapse accident. On the other side, if jack supports are installed at too narrow intervals, costs increase.

The existing method of inspecting the jack supports installation intervals at construction sites is time-consuming work because inspectors have to go to the site and measure the interval between the jack supports by devices like a ruler, but generally check by their eye. In addition, the existing method may lead to a collapse accident due to inaccurate supervision.

Therefore, this paper conducted the preliminary study on the automatic jack support installation interval measurement model using images. The proposed model consists of two parts; one part is the jack support segmentation in an image, and another part is the installation interval measurement. The results of this study can contribute to ensuring the construction quality of jack supports and further preventing building collapse accidents.

2. Methodology

The process of this study is shown in Fig. 1. Instance segmentation was preceded to extract the coordinates of the jack support from the image. In the instance segmentation step, reference points for measuring the distance between jack supports were extracted, and 3D coordinates were converted from 2D coordinates using camera calibration. Finally, the distance between the two reference points in the real world was measured.

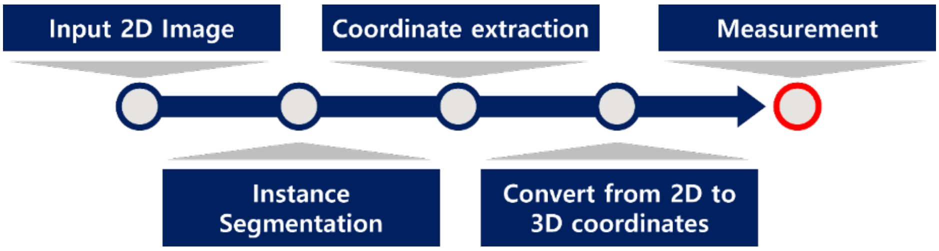

Fig. 1. jack support installation interval measurement model process

2.1. Jack support segmentation

For the jack supports segmentation in image, the recently released YOLOv8 [2] model with the best performance was used. We labelled image dataset with two classes of jack support and background as shown in Fig. 2. In the image segmentation step, jack support coordinate values were extracted. As a reference point for measuring the distance between jack supports, the bottom mid-points of the extracted coordinate values were used as the reference point.

(a) (b)

Fig. 2. (a) original image; (b) labeling image

2.2. Measurement

The next step is to measure the distance between the jack supports. It is necessary to convert the 2D points extracted in the previous step to 3D coordinates in the real world. Camera calibration was used to extract the focal length required for conversion into 3D coordinates in units of pixels. The angle and height of the camera required for conversion were measured in advance by installing the camera on a tripod. In order to convert a 2D point ($\bar{x}$, $\bar{y}$) on the image into a 3D point (X, Y, Z) in a real world, it was calculated as shown in Equations 1 and 2. In here, the y coordinate representing the height is set to 0 because the bottom point of the jack supports is on the floor.

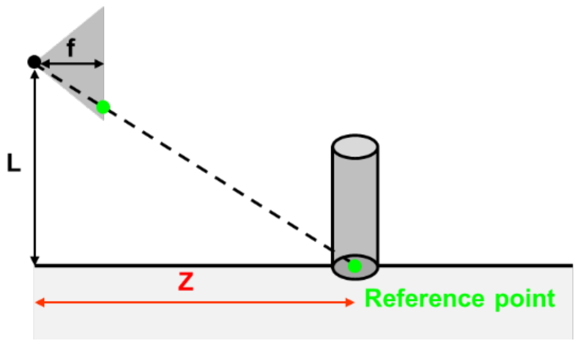

Fig. 3. object localization

$$Z = \frac{\bar{z}}{\bar{y}} L \quad (1)$$

$$X = \frac{\bar{x}}{\bar{y}} Z \quad (2)$$

X is a value in a direction of the horizontally across the scene, Z is a value in a direction of the front of camera, L is the camera height, $\bar{x}$ is a horizontal value in image, $\bar{y}$ is a vertical value in image, and $\bar{z}$ is a camera focal length.

Finally, the distance (D_{ij}) between the reference points P_i and P_j of the i^{th} and j^{th} jack support was calculated as in Equation 3. X_i and Y_i is the 3D coordinate of P_i in a real world.

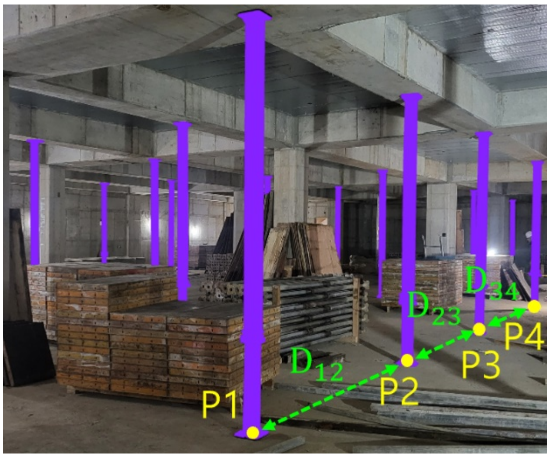

Fig. 4. example of jack support measurement

$$D_{ij} = \sqrt{(X_i - X_j)^2 + (Z_i - Z_j)^2} \quad (3)$$

3. Experimental Study

We tested the validity the proposed model. The accuracy of the jack support segmentation algorithm was tested and then the accuracy of measurement algorithm was tested in the laboratory. Finally, jack supports installation intervals in construction site was measured using the proposed model.

3.1. Test result of jack support segmentation algorithm

To test the effectiveness of the instance segmentation algorithm, jack supports installed in the field were used. First, the 20 datasets for learning the segmentation model were classified into 16 training datasets, 2 validation datasets, and 2 test datasets. The parameters of the learning model were set to 2,000 epochs, batch size to 16, and learning rate to 0.01. As a result of model training, as shown in Fig. 6 below, 1,971 epochs showed the lowest loss and highest precision. In addition, the validation results applied for each epoch showed the best results at 1,971 epochs like the training results. The mAP of the best model was 90.4%.

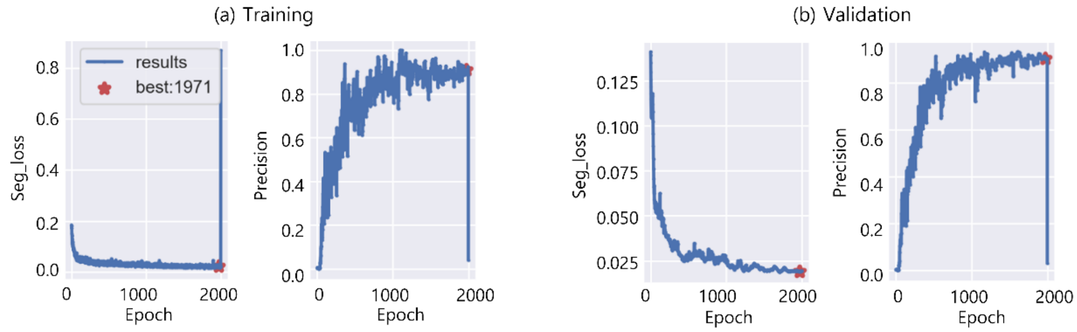

Fig. 5. (a) segmentation model training results; (b) verification results

The test results of the jack support segmentation algorithm is shown in Fig. 6.

Fig. 6. segmentation model results

3.2. Test result of measurement algorithm

To test the measurement accuracy of the measurement algorithm, the floor tiles of the laboratory corridor were used as target. The measurement test process is as follows. First, mount the smartphone on a tripod at the height of 1.0 m and take a picture in a direction of the front. Measure the height from the floor to the camera lens to convert 2D coordinates to 3D coordinates. Then, calibrate the camera to get the correct focal length. The size of floor tiles has measured a total of 4 times to determine the accuracy of measuring the spacing of corridor tiles using the images. The error rate was calculated by comparing the measured distance with the correct answer distance using the proposed model, and the accuracy was measured by calculating the average error rate. The measured image and the correct answer image are shown in Fig. 7.

Fig. 7. (a) corridor tile spacing ground true; (b) corridor tile spacing model measurement result

A tile size of the corridor was 0.6m, and the test results are as shown in Table 1. When the tile measured by the camera was 3m away, it showed an error rate of -0.3% at 0.602m, showed an error rate of -0.3% at 0.592m when it was 3.6m away, and showed an error rate of 0.8% at 0.595m when it was 4.2m away. When it was 4.8m away, it was 0.592m, showing an error rate of 1.3%. As a result of the measurement test of the corridor tiles, the measurement accuracy was 99.2%.

Table 1. Measurement error rate.

Distance from camera	Ground true	Measurement	Error
3m	0.6m	0.602m	- 0.3%
3.6m	0.6m	0.592m	1.3%
4.2m	0.6m	0.595m	0.8%
4.8m	0.6m	0.592m	1.3%

3.3. Test result of the proposed model

To test the effectiveness of the proposed model, we tested the proposed model to the images of jack support installation sites. The focal length was extracted through camera calibration. The angle of the camera was directly measured, and the height of the camera was calculated by measuring from the mid-point of the camera lens to the bottom. And then, jack supports were segmented by the segmentation algorithm and reference points of jack supports were extracted. Finally, the distance was measured based on the reference points by the measure algorithm. The result of measuring the installation interval of the jack support through the proposed model is shown in Fig.8.

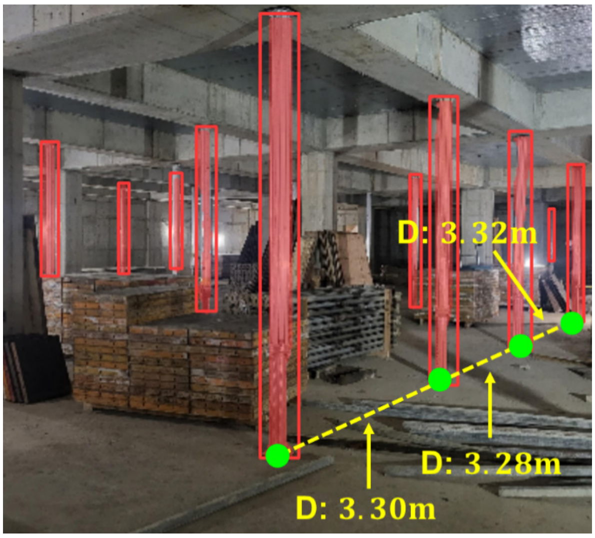

Fig. 8. test result of the proposed model

4. Conclusions

In this study, an image-based jack support installation interval measurement model was proposed. The proposed model can automatically measure the jack support installation interval from the image. As a result of experimental study, the jack support segmentation algorithm was 90.4% mAP and the accuracy of the measurement algorithm was 99.2%. This result of this study would contribute to prevent collapse accident which may occur due to inaccurate jack support installation. For the further research, we will research the automated camera calibration algorithm to gain the angle and height of the camera.

Acknowledgements

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References

[1] Temporary structure. Korea Occupational Safety and Health Agency. Accessed: November 10, 2016. [Online]. Available: https://www.kosha.or.kr/kosha/data/terminologyDictionary.do?mode=view&articleNo=394811&article.offset=0&articleLimit=10&srSearchVal=%EA%B0%80%EC%84%A4%EA%B5%AC%EC%A1%B0%EB%AC%BC&srSearchKey=article_title.

[2] Oh, Tae Keun, Kim, Yongon, Lee, Myeong-Gu, Paik, Shinwon, Woo, In-Sung, and Song, Chang-Geun, “A Study on the Design Change of High-Risk Temporary Structures,” Journal of the Korean Society of Safety, vol. 29, no. 1, pp. 37–40, Feb. 2014.

[3] Park, Se Hwan, Youm, Minkyo, Kim, Haksun, Cho, Jung Ho, Kim, Junkyeong. "Development of Wireless Load Cell System for Jack Support using Bluetooth Beacon" Journal of the Korean Society of Civil Engineers , (2020) : 727-728.

[4] YOLO by Ultralytics (Version 8.0.0). Jocher, G., Chaurasia, A., & Qiu, J. Accessed: November 1, 2023. [Online]. Available: https://github.com/ultralytics/ultralytics

A ROADMAP TO A SHARED VISION FOR PLATFORMS: THE MOTIVATIONS AND ROLES OF STAKEHOLDERS IN THE TRANSFORMATION FROM PROJECTS TO PLATFORMS

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Abstract

In recent years, 'platform' has emerged as a buzzword for business. Despite widespread usage, there remains ambiguity in its meaning. Strategically, platforms capitalize on the advantages of commonality and have been successfully applied across multiple industries to deliver mass-customized products, increasing customer choice while maintaining efficient and effective production methods. It is known that the early involvement of stakeholders enables the platform logic, however that requires redefining their roles and motivations in the platform ecosystem. This paper aims to envisage redefined roles for each stakeholder in the construction value chain to create a shared vision roadmap by understanding their motivations for moving towards a platform ecosystem and how their engagement model will be changed. Four enterprises in Australia, that represent key stakeholders of the construction value chain, were selected for knowledge elicitation through individual discussions. The perspective pitches for the primary stakeholders comprise developers, general and specialized contractors, designers and engineers, while the rest of the value chain is grouped under associated stakeholders. In an attempt to define the new roles for the different stakeholders of the platform ecosystem, there emerged a shared vision that might enable a shift towards the platform approach. The intent for moving value-adding products and services upstream, expanding contribution to the value chain, continuous improvement through data-driven insights, seamless collaboration in a partnering environment and early prototyping were shared across stakeholder groups. A changed nature of engagement was observed where the general contractor ceased to be the single point of engagement with the associated supply chain actors; this role was most likely to be taken up by the developer or the platform consultant. For a longer study, the value chain actors in terms of financiers (upstream) and asset managers (downstream) are required to be included in the value chain and their motivations and roles explored.

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Keywords: construction, platform, roadmap, stakeholders, ecosystem.

1. Introduction

Platforms represent a collection of assets that are shared by a set of products; comprising components, processes knowledge and people [1]. While platforms originated with manufacturers using product platforms, today, technological platforms underpin many of the world's most valuable companies and it is increasingly being considered that platforms have the potential to create value in the construction sector [2]. Platforms establish commonality with the strategic intent of achieving revenue benefits through finding and serving niche requirements, cost reduction by leveraging economies of scale and risk reduction through increased quality and reduced susceptibility to changing environments [3]. While academia and industry have focussed on the efficiency and productivity of platforms, it is now being demonstrated that platform-thinking also enables new possibilities to effectively deliver design value to end-users [4]. Design for Manufacture and Assembly (DfMA) is the predecessor of the platform approach in construction; however, when baked together they unlock the true potential of digital design and simulation using computational design processes to create standardisation at component level but retain design flexibility at the asset level [5]. Given this, there is a need to investigated the implications of the emergence of platform ecosystems for each stakeholder in the construction value chain. The emergence of platform ecosystems necessitates construction businesses to consider how they can participate in a larger ecosystem as opposed to focusing solely on internal operations [6].

This paper aims to envisage redefined roles for each stakeholder in the construction value chain to create a shared vision roadmap by understanding their motivations for moving towards a platform ecosystem and how their engagement model will be changed. Four enterprises in Australia, that represent key stakeholders of the construction value chain, were selected for knowledge elicitation through individual discussions. The perspective pitches for the primary stakeholders comprise developers, general and specialized contractors, designers and engineers, while the rest of the value chain is grouped under associated stakeholders. In an attempt to define the new roles for the different stakeholders of the platform ecosystem, there emerged a shared vision that might enable a shift towards the platform approach.

2. Emergence Of Product Platforms

The earliest definitions of product platforms were "… *the collection of assets that are shared by a set of products*" [1] and "…a set of common components, modules, or parts from which a stream of derivative products can be efficiently created and launched" [7]. Product design was traditionally viewed as a singular, isolated activity in manufacturing. According to Meyer and Lehnerd [7], this traditional approach understated the potential for "commonality, compatibility, standardisation, or modularisation among different products and product lines." Manufacturers developed product platforms to enable the creation of simple product lines that could share elements of a common family structure in response to this challenge. Utilising a product platform allows for the efficient development of differentiated products through the sharing of physical components and production processes [8]. By summing up their definition as "a collection of basic assets that are reused to produce a competitive advantage," Kristjansson, et al. [9] highlighted that "reuse" was a prevalent theme across product platform definitions. The product platform concept ultimately enables organizations to effectively adjust to shifting market conditions and needs for mass customization, all while enhancing manufacturing and design efficiency via a mind-set centered on constant process improvements [8].

The construction sector has three primary 'domains': the client domain, the project domain and the product domain; Each domain plays a crucial role in the construction of the built environment but the way they interact frequently leads to inefficiencies that may be solved by the emergence of product platforms in some circumstances [2]. Sweden is one of the world's leading producers of industrially built housing and Swedish success stories are dominant in literature about product platforms in construction [8]. Literature also cites Japan as a country where product platforms have been utilised in construction. The steady development of the sector in Japan was a consequence of "a combination of continuous incremental and disruptive innovations and a unique socio-economic and socio-cultural environment" [10]. However, prominent examples in literature always start with Boklok. Swedish multinational contractor Skanska collaborated with IKEA to develop Boklok, a low-cost housing delivery system using a product platform aimed at critical workers with restricted wages. Using the IKEA brand, Boklok established a strong and consistent market identity that aims to serve the general public with high-quality, well-designed housing [11].

3. Emergence of Platform Ecosystems

Platform as a concept is evolving in current applications; there has been a shift from viewing platforms as purely internal company structures as was the case of product platforms to considering them on a more industry-wide scale [8]. These platforms erode the traditional line of demarcation between businesses (companies) and the marketplace [6]. In such cases, a foundational platform created by a company allows other companies to build upon it; thus, here the platform is neither a market nor a business (company), but something entirely novel [12]. The concept of 'platform ecosystems' is derived from 'business ecosystems' which is no means is new; business and economics theorist Moore [13] proposed that, '… a company be viewed not as a member of a single industry but as part of a business ecosystem that crosses a variety of industries. In a business ecosystem, companies co-evolve capabilities around a new innovation: they work cooperatively and competitively to support new products, satisfy customer needs, and eventually incorporate the next round of innovations." In the context of platforms, such an integrative framework was seen in the work of Gawer [14] where platforms are classified into internal platforms, supply chain platforms and industry platforms. Internal platforms are managed through hierarchy and have closed interfaces and specifications are shared within the firm, but not disclosed externally. Supply chain platforms are managed through contractual relations between supply chain member organisations; therefore, interfaces are selectively opened and specifications are exclusively shared across the supply chain. Industry platforms are managed through governance mechanisms (which sometimes can be pricing) and have open interfaces that allow sharing specifications with complementors.

4. Research Approach

This section will explain the selection criteria, data collection and analysis protocols of the knowledge elicitation through individual discussions conducted in this paper.

4.1 Selection criteria

Four enterprises in Australia were selected for knowledge elicitation through individual discussions each representing a stakeholder group in the construction value chain. The first company (CS1) has around 1,000 employees, operates throughout Australia, and provides specialist building services. The second company (CS2) has around 15,000 employees, operates throughout 18 countries, the company is the biggest manufacturer in Australia and is a top supplier globally, specializing in producing steel products and providing solutions for building and construction markets. The third company (CS3) has around 1,000 employees, operates throughout Australia, and it is a leader in technology implementation, product development and quality control, with a world-class manufacturing capacity and environmental standards that underpin a commitment to sustainably grown timber production and supply in Australia. The last company (CS4) has around 5,000 employees, operates throughout Australia and Asia, the company is a global leader in residential construction, building materials and property development. As nominated by the companies, one or two representatives of each company were interviewed. The interviewee details, experiences, and stakeholder groups are shown in **Table 1**.

Table 1. The participant details, experiences, and stakeholder groups for knowledge elicitation through individual discussions

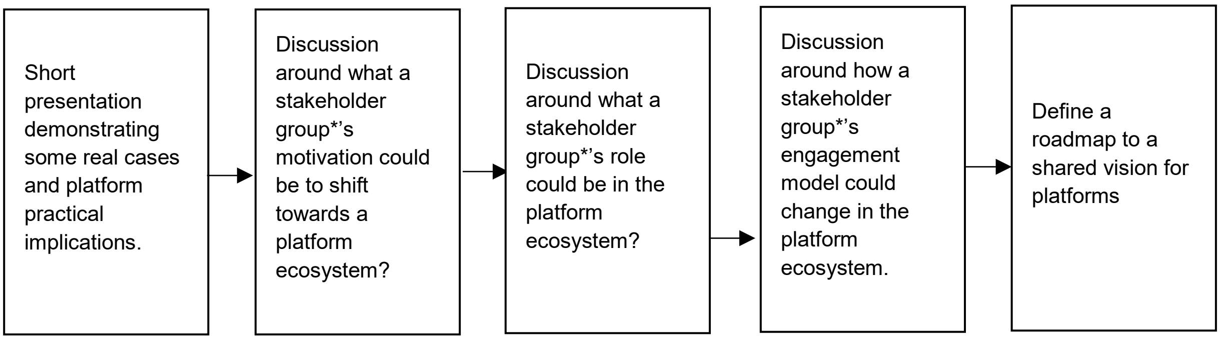
Code	Experience	Area of Experience	Stakeholder group
SDD	20+	Building services-integrated solutions	Specialised Contractor/ Designers and Engineers
GM	15+	Construction management	Developer/
SM	15+	Construction Business Development	Developer/ Material Processing
EM	15+	Engineering management of mega projects	Material Processing/ Component Manufacturers
BDL	20+	Construction Business Development	Material Processing/ Component Manufacturers
ETL	15+	Digital Transformation	Material Processing/ Component Manufacturers

SDD – Strategic Development Director
GM – General Manager
SM – Senior Manager
EM – Engineering Manager
BDL – Business Development Lead
ETL – Enterprise Transformation Leader

The primary stakeholders for the perspective pitches are developers, general contractors, specialized contractors, and designers and engineers. The other stakeholders of the value chain are considered associated stakeholders. The authors acknowledge that there are some blind spots in the value chain actors presented in this paper in terms of financiers (upstream) and asset managers (downstream) who also will play critical roles in the platform ecosystem; however, during the course of this scoping paper, it was not possible to collect primary data from these actors.

4.2 Data collection

Data were collected using semi-structured interviews. The selected organizations who represent key stakeholders of the construction value chain nominated the most suited role to be interviewed. The interviews were conducted online via Zoom™ and recorded. The inspiration behind this shared vision roadmap originated in the thought starters presented in the McKinsey report *'The next normal in construction: How disruption is reshaping the world's largest ecosystem'* by Ribeirinho, et al. [15]. **Fig. 1.** illustrates how knowledge elicitation through individual discussions was conducted for this research.



* *Stakeholders groups include developers, specialized contractors, designers and engineers, while the rest of the value chain is grouped under associated stakeholders.*

Fig.1. Method for conducting knowledge elicitation through individual discussions

4.3 Data analysis

The knowledge elicitation discussions were qualitatively analyzed with respect to the research objectives. The verbatim transcripts were de-identified, interpreted, and labelled to be uniquely identifiable for each interview and used as the unit of analysis. The outputs from the knowledge elicitation discussion were utilized to define the motivation, roles and engagement models for the different stakeholder groups in a platform ecosystem. In doing so, there emerged a shared vision that might enable a shift towards the platform approach as explained in the following section.

5. Findings

This section will present redefined roles for each stakeholder in the construction value chain to create a shared vision roadmap for platforms consisting of their motivations and roles. How would their engagement model change? This section is structured into four sub-sections; developers, designers and engineers, specialised contractors, and associated supply chain actors.

5.1 Developers

What could a developer's motivation be?

A developer's primary requirement from a platform is seamless evaluation of prospective sites through automated feasibility analysis. If a platform could help decide whether a site is valuable to acquire and can be turned into a positive business, it would benefit the developer immensely. What a developer wants next is for a platform to enable partnering up with other actors on the engineering, design, and supply side of the value chain. Developers also would be motivated by the idea of accelerating sustainable building methods by focussing on early involvement of supply chain actors through the platform.

A developer is further motivated by the promise of connectivity; a platform can take the feasibility model into production solidifying the financial backbone of the project. Moreover, if these steps occur in a collaborative platform with a partnering environment, it would help run iterations of different scenarios where developers can almost have a platform-based product and then back calculate to identify the lots that fit best with it. In the long term, large companies could leverage economies of scale through a standardised kit of parts, continuously made efficient by feeding projects involving similar construction types and similar geographies.

What could a developer’s role be?

As a key player in the construction industry, a developer's role is multifaceted and critical to the success of any project. One of the most important responsibilities of a developer is to enable the horizontal integration of the supply chain actors towards the platform approach and initiate early prototyping with preconstruction activities integrated into the contractual arrangements of specialised contractors and suppliers. To further support this objective, a developer should enable an end-to-end information flow to support project delivery from feasibility and acquisition through to design and construction. Continuously improving the design (standardised kit of parts) and construction processes through the capture and analysis of operational data is also essential. Finally, a developer should seek to be more circular through design, material, process optimization and automation wherever possible in the project

How would a developer’s engagement model change?

A developer might now engage with more supply chain actors than just the main contractor. This interaction might be facilitated by a digital platform (marketplace). The engagement could start earlier to enable prototyping and injecting platform DNAs into existing products and processes.

5.2 Designers and engineers

What could a designer / engineer’s motivation be?

The primary motivation of designers and engineers is to better utilize their digital capabilities to streamline the design and delivery process. In a completely BIM and digital engineering enabled setup, designers and engineers have the capacity to contribute to a larger part of the value chain. For example, using parametric design, they can instantly have a fully resolved model that can be manufactured and constructed. This places the designers and engineers in the most suited position to become go-to partners for design-to-manufacture.

Designers and engineers are also well placed to assume an advisory role of the platform consultant that drive the platform approach for a client right from the early prototyping stage to training the specialised contractors for site assembly. This transforms the commercial model for designers and engineers from a typical hourly rate to outcome-based percentage of cost.

Designers and engineers might also be motivated to become technology providers enabling the platform approach. The platform approach benefits from bringing value adding services upstream; given this by becoming technology providers, designers and engineers can license out their proprietary platform technology to gain scale and internationalize. This could create an opportunity for them to build their business around data through advanced analytics.

What could a designer / engineer’s role be?

To effectively utilize the platform approach, designers and engineers should develop strong customer relationships or a deep understanding of customer requirements to utilise the platform approach in the best possible way. They should also have a good knowledge and understanding of systemisation, commonality strategy (commonality in processes and enablers, not just physical components). Additionally, they must establish routines to carry digital models through to fabrication and create a dynamic marketplace for diverse supply chain actors to contribute to the platform ecosystem with a low barrier of entry. To support this, train associated supply chain actors based on the knowledge gained from early prototyping is needed, as well as, continuous improvement of by obtaining data-driven insights. Finally, they should embed circularity through design, material, process optimisation and automation.

How would a designer / engineer’s engagement model change?

Designers and engineers might now engage with more supply chain actors than just the main contractor. The engagement could start earlier to enable prototyping and injecting platform DNAs into existing products and processes.

5.3 Specialised Contractors

A specialised contractor is somebody who simply does what is documented; it can be assembling on site, procuring materials or just supplying labour. Specialised contractors can also deliver a turnkey outcome including complete design and construction and be responsible for the safe performance and operation of the asset. In other words, specialised contractors mostly deliver a subcomponent of the superstructure; they are usually downstream in the value chain and typically do not initiate, design or manage projects in their entirety.

What could a specialised contractor's motivation be?

Specialised Contractors are primarily motivated to take advantage of the digitalisation of design, construction and procurement to move upstream in the value chain in order to avoid the old school queueing up and improve their market position. Specialised contractors are also motivated towards the platform approach as it could enable collaboration across different stakeholders through workflows in an aggregator sense but also in a single stream sense (for their continuous improvement). Achieving economies of scale is also a motivation for specialised contractors; when a specialised contractor develops a platform solution, it opens up multitude of opportunities for them to replicate it across the commercial building sector (wherever a platform approach is implemented). As seen in the case of developers, specialised contractors are also looking for a trustful partner environment facilitated by the platform through sharing of Intellectual Property (IP) where all parties work upfront diligently towards project goals. Finally, safety is an important driver for motivating specialised contractors towards the platform approach as most of them play a key role in site assembly.

What could a specialised contractor's role be?

To facilitate prototyping (mock-ups) and enable early involvement in the value chain, specialized contractors should be engaged at an early stage. They also should increase the level of modular designs and offsite production in order to limit time on site and enable upstream integration into the value chain through digital interfaces thereby improving bargaining power over general contractors, distributors and component manufacturers. Achieving operational excellence through continuous improvement of design, logistics and assembly is another important responsibility of specialized contractors. Finally, they should facilitate the reduction of embodied and operational carbon through design optimisation and the use of offsite facilities.

How would a specialised contractor's engagement model change?
The engagement model might not change to a great extent but engagement through digital interfaces might increase. The engagement model might become more balanced through early involvement and equitable partnerships.

5.4 Associated Supply Chain Actors

The associated supply chain actors comprise material processors, component manufacturers, material distributors and logistics players. Such associated supply chain actors typically have a chain of business archetypes upstream to downstream. For example, they might produce a material, add value to it, provide value added products, provide total solutions or provide a channel for the distribution of the material.

What could their motivation be?

These associated supply chain actors are motivated by the notion that a platform approach can enable them to not only optimise their material processing, but also towards contributing to better buildings through product innovation. They typically have numerous disjointed initiatives; the platform approach creates an opportunity to operate or participate in an end-to-end offering. The future ready state from their perspective is not in selling material or products anymore, it is in participating in that whole end-to-end value generation through critical enablers like digital and strategic marketing. The associated supply chain actors are motivated to shift to a platform approach as it can help them integrate businesses that they have acquired over time in the form of a shared services model. The peak of this integration, however, sits beyond the organizational boundaries in a digital marketplace that is self-serving of their own products. Trusted information sharing among the value chain players could enable better demand forecasting and ultimately enhance the total value of the system. Further, the platform approach comes with the promise that these associated supply chain actors can set a clear decarbonization pathway and contribute to the circular economy which becomes one of their biggest motivations and competitive advantage.

What could their role be?
Companies must develop a capacity to inject platform DNA into an existing suite of products and offer solutions that can integrate with a platform ecosystem in order to strengthen their engineering capabilities in product development through the integration of digital tools towards an end-to-end offering. Improving customer experience is essential, and companies can achieve this by understanding how to address their key challenges through digital interactions. Additionally, they must invest in the upskilling of a platform champion; a person who has the technical skills, theoretical knowledge and the motivation to lead and guide teams towards the platform approach. Finally, companies should advocate for products that embed circularity in the value chain.

How would their engagement model change?

Detailed technical review and consultations between the associated supply chain actors, the developer and platform consultant to evaluate if products from an existing catalogue can be repurposed for the platform approach.

6. Discussion of findings

The redefined roles of the stakeholder groups presented in this research align with the narrative that platform thinking erodes the traditional line of demarcation between businesses (companies) and the marketplace [6] as it necessitates construction businesses to consider how they can participate in a larger ecosystem as opposed to focusing solely on internal operations. To support new products, meet consumer demands, and finally adopt the next round of innovations, they must collaborate and compete [12]. The platform ecosystem provides a framework for understanding how companies can co-evolve capabilities and co-create value to leverage the capabilities of a broader engagement network among the construction value chain stakeholders [5]. Real industry cases also complement the findings of this research. In the much talked about Forge, that has been discussed by platform enthusiasts globally, the aim was to potentially create a dynamic marketplace for diverse supply chain contributors with a low barrier of entry (a positive supply chain competitive environment). Another striking difference in the case of the Forge, while there is a platform consultant (Bryden Wood), a developer (Landsec), a construction management expert (Sir Robert McAlpine and Mace JV) and several key trade contractors and suppliers (J Coffey Construction, N G Bailey, Tata Steel, Schneider Electric), there is no explicit mention of a general contractor. Through a different approach from the Forge, platform-based companies such as the Volumetric Building Companies are playing the role of a general contractor with an end-to-end value chain and companies like Intelligent City, who have originated with an architecture background are also now taking up roles similar to the general contractor., Despite this, the general contractor perhaps has the biggest opportunity in the platform ecosystem but would need to redefine their role based on their motivation and scale.

In an attempt to define the new roles for the different stakeholders of the platform ecosystem, there emerged a shared vision that might enable a shift towards the platform approach. The intent for moving value adding products and services upstream, expanding contribution to the value chain, continuous improvement through data-driven insights, seamless collaboration in a partnering environment and early prototyping were shared across stakeholder groups. A changed nature of engagement was observed where the general contractor ceased to be the single point of engagement with the associated supply chain actors; this role was most likely to be taken up by the developer or the platform consultant.

7. Conclusions And Future Work

The primary contribution of this paper was to develop a shared-vision roadmap for future platform-based building participants when moving from project-based work approaches to a platform-based approach. Prior to this paper, no research had investigated the implications of the emergence of a platform ecosystem for each stakeholder in the construction value chain. The emergence of platform ecosystems necessitates construction businesses to consider how they can participate in a larger ecosystem as opposed to focusing solely on internal operations.

The theoretical contribution of this research was to understand and redefine roles for each stakeholder in the construction value chain to create a shared vision roadmap by understanding their motivations for moving towards a platform ecosystem and how their engagement model will be changed. Four enterprises in Australia, that represent key stakeholders of the construction value chain, were selected for knowledge elicitation through individual discussions. The perspective pitches for the primary stakeholders comprise developers, general and specialized contractors, designers and engineers, while the rest of the value chain is grouped under associated stakeholders. Across stakeholder groups we observed an intent for moving value-adding products and services upstream, expanding contribution to the value chain, continuous improvement through data-driven insights, seamless collaboration in a partnering environment and early prototyping were shared across stakeholder groups.

The practical contribution of this research leads to the progression of companies towards the emergence of integrative frameworks of platform ecosystems as a changed nature of engagement was observed where the general contractor ceased to be the single point of engagement with the associated supply chain actors; this role was most likely to be taken up by the developer or the platform consultant. Despite the relevance of the findings of this paper, there are some blind spots in the value chain actors in terms of financiers (upstream) and asset managers (downstream) who also will play critical roles in the platform ecosystem; however, during the course of this scoping study, it was not possible to collect primary data from these actors. For a longer study, these actors are required to be included in the value chain and their motivations and roles explored.

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References

[1] D. Robertson and K. Ulrich, "Planning for product platforms," *Sloan management review,* vol. 39, no. 4, pp. 19-31, 1998, doi: https://repository.upenn.edu/oid_papers/266.

[2] L. Mosca, K. Jones, A. Davies, J. Whyte, and J. Glass, "Platform Thinking for Construction," in "Transforming Construction Network Plus, Digest Series," The United Kingdom, 2020. [Online]. Available: https://www.ucl.ac.uk/bartlett/construction/sites/bartlett/files/digest-platform-thinking-for-construction.pdf

[3] Construction Innovation Hub, "The Product Platform Rulebook [Edition 1.2]," UK Research and Innovation, United Kingdom, 2023. [Online]. Available: https://www.constructioninnovationhub.org.uk/media/nfdfyhoj/cih-product-platform-rulebook-edition-12.pdf

[4] D. Maxwell and M. Aitchison, "Design-value in the platform approach," in *25th Annual Conference of the International Group for Lean Construction*, Heraklion, Greece, 2017, pp. 349-356, doi: https://doi.org/10.24928/2017/0033.

[5] Bryden Wood, "Bridging the gap between construction + manufacturing," Construction Innovation Hub, United Kingdom, 2018. [Online]. Available: https://www.cdbb.cam.ac.uk/news/2018MarchPlatforms

[6] A. Tiwana, *Platform ecosystems: Aligning architecture, governance, and strategy*. Newnes, 2013.

[7] M. H. Meyer and A. P. Lehnerd, *The power of product platforms: Building Value and Cost Leadership*. Simon and Schuster, 1997.

[8] D. W. Maxwell, "The Case for Design-Value in Industrialised House Building Platforms: Product to Ecosystem," Doctor of Philosophy, Sydney School of Architecture, Design and Planning, The University of Sydney, 2018. [Online]. Available: http://hdl.handle.net/2123/18641

[9] A. H. Kristjansson, T. Jensen, and H. P. Hildre, "The term platform in the context of a product developing company," in *DS 32: Proceedings of DESIGN 2004, the 8th International Design Conference*, Dubrovnik, Croatia, May 18 - 21 2004, doi: https://www.designsociety.org/download-publication/19770/the_term_platform_in_the_context_of_a_product_developing_company.

[10] M. Höök, "Lean culture in industrialized housing: a study of timber volume element prefabrication," Doctor of Philosophy, Department of Civil, Environmental and Natural Resources Engineering, Structural and Construction Engineering, Luleå University of Technology, 2008. [Online]. Available: https://www.diva-portal.org/smash/record.jsf?pid=diva2%3A998900&dswid=-8831

[11] J. Lessing and S. Brege, "Industrialized building companies' business models: Multiple case study of Swedish and North American companies," *Journal of Construction Engineering and Management,* vol. 144, no. 2, p. 05017019, 2018, doi: https://doi.org/10.1061/(ASCE)CO.1943-7862.0001368.

[12] K. S. Rahman and K. Thelen, "The rise of the platform business model and the transformation of twenty-first-century capitalism," *Politics & society,* vol. 47, no. 2, pp. 177-204, 2019, doi: https://doi.org/10.1177/0032329219838932.

[13] J. F. Moore, "Predators and prey: a new ecology of competition," *Harvard business review,* vol. 71, no. 3, pp. 75-86, 1993, doi: http://blogs.harvard.edu/jim/files/2010/04/Predators-and-Prey.pdf.

[14] A. Gawer, "Bridging differing perspectives on technological platforms: Toward an integrative framework," *Research policy,* vol. 43, no. 7, pp. 1239-1249, 2014, doi: https://doi.org/10.1016/j.respol.2014.03.006.

[15] M. J. Ribeirinho *et al.*, "The next normal in construction: How disruption is reshaping the world's largest ecosystem," McKinsey & Company: Zurich, Switzerland, 2020. [Online]. Available: https://www.mckinsey.com/capabilities/operations/our-insights/the-next-normal-in-construction-how-disruption-is-reshaping-the-worlds-largest-ecosystem

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A STATISTIC RESEARCH ON CHANGES IN THE NUMBER OF BIDDERS FOR BUILDING WORKS PROJECTS USING THE DATABASE IN THE KANTO REGION

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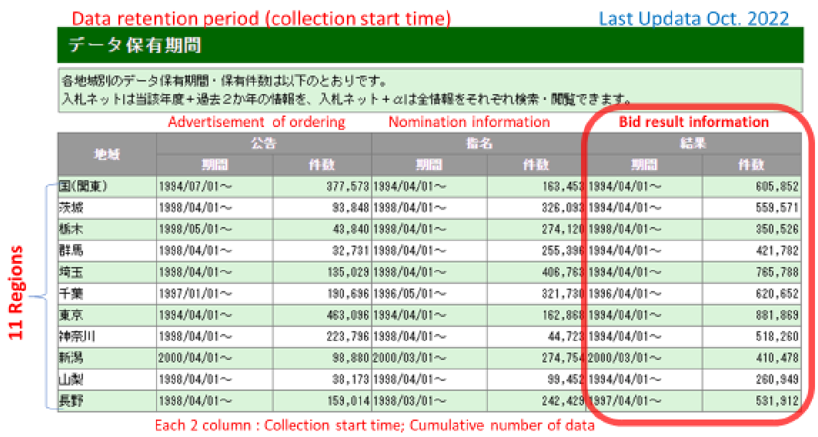
Abstract

In order to ensure the transparency of public works, disclosures of competitive bidding results are widely practiced in accordance with Japanese law. The purpose of research is to collect bidding results data in chronological order and to observe fluctuations. The data collection range is the Kanto region including the Tokyo metropolitan area. We targeted bidding result information of building works over 100,000 data after 2000 fiscal year. First, we surveyed the characteristics such as type, region, scale of construction, and bidding method. Second, we analyzed trends in the number of bidders and successful bid rates, which were calculated by 5 owner agency categories. Over the past 20 years, Japan's public procurement market has undergone a major system change from designated bidding to general competitive bidding. There are many construction markets where the number of participants per bid has decreased over time. Especially in Tokyo, not a little bid ended up with single bidder, which exposed the challenges of competition policy. In 2017 to 2018, the Tokyo Metropolitan Government had tried to cancel the project that was a single bidder, but finally gave up due to disturbance to the implementation of public works projects and the oppositions from the industry. In this paper, by analyzing bidding result data, we have described in detail the situation, such as when and in what layer the number of single bids occurred. Other major findings are as follows: 1) Although the number of bidders tends to decrease at each owner, there are differences depending on the bidding conditions. 2) Looking at the long-term transition of the successful bid rate, it dropped around 2009 to 2011 after the Lehman Shock. 3) In many cases, it was also observed that as the number of bidders decreased, the successful bid rate increased.

Keywords: big data, competitiveness, only one offer, single bid, tender, time series analysis

1. Research purpose and scope



地域	公告		指名		結果	
	期間	件数	期間	件数	期間	件数
国(関東)	1994/07/01～	377,573	1994/04/01～	163,453	1994/04/01～	605,852
茨城	1998/04/01～	93,848	1998/04/01～	326,093	1994/04/01～	559,571
栃木	1998/05/01～	43,840	1998/04/01～	274,120	1998/04/01～	350,526
群馬	1998/04/01～	32,731	1998/04/01～	255,396	1994/04/01～	421,782
埼玉	1998/04/01～	135,029	1998/04/01～	406,763	1994/04/01～	765,788
千葉	1997/01/01～	190,696	1996/05/01～	321,730	1996/04/01～	620,652
東京	1994/04/01～	463,096	1994/04/01～	162,868	1994/04/01～	881,869
神奈川	1998/04/01～	223,796	1998/04/01～	44,723	1994/04/01～	518,260
新潟	2000/04/01～	98,880	2000/03/01～	274,754	2000/03/01～	410,478
山梨	1998/04/01～	38,173	1998/04/01～	99,452	1994/04/01～	260,949
長野	1998/04/01～	159,014	1998/03/01～	242,429	1997/04/01～	531,912

* This database need fee for membership.

Fig. 1. The database used (Source: https://www.nikoukei.co.jp/PurchaseItems/PurchaseNyusatunetAlpha).

It would be said that bidding results reflect the competitive situation of each market at that time. We believe that it is necessary to broadly collect, carefully monitor, and understand such long-term time-series information. In particular, the number of bidders is an important indicator. Our research used bidding result information that has been collected over many years by a construction newspaper company. Much of the information is the result of painstaking collection of data released by public owner organizations under Japanese law: *Act for Promotion of Proper Tendering and Contracting for Public Works (Act No.127 of 2000)*. They are big data of 5.92 million rows x 36 variables for 11 regions of Kanto: the central part of Japan, including the Tokyo metropolitan area. (see Fig. 1)

In the analysis below, various ordering agencies are grouped into five broad categories - these are national, prefectural, municipal, related public organizations and private sector. And the target was narrowed down under 4 conditions below: (1) Bidding date is after 2001 so, the analysis period: Apr. 2001 to Oct. 2022. (2) The work category limited to construction work, i.e. it does not include bids for consultancy work, etc. (3) The successful bid amount is 5 million yen or more. (4) Bidding method is limited to general competition or designated competition (not include negotiations, etc.). After all, number of analysed data limited to 142,672 bidding results. In this study, we mainly examined following 3 points:

- Changes in bidding competition methods for more than 20 years in Japan
- Changes in the number of bid participants in construction bidding
- Trends and changes in single bids, and the relationship with the successful bit rate

2. Coverage of the database

The coverage of this database turned out to be high based on the statistics: Turnover-based values in public sector tables of general construction statistics obtained from eStat, which is a comprehensive statistical website provided by the Japanese Government.

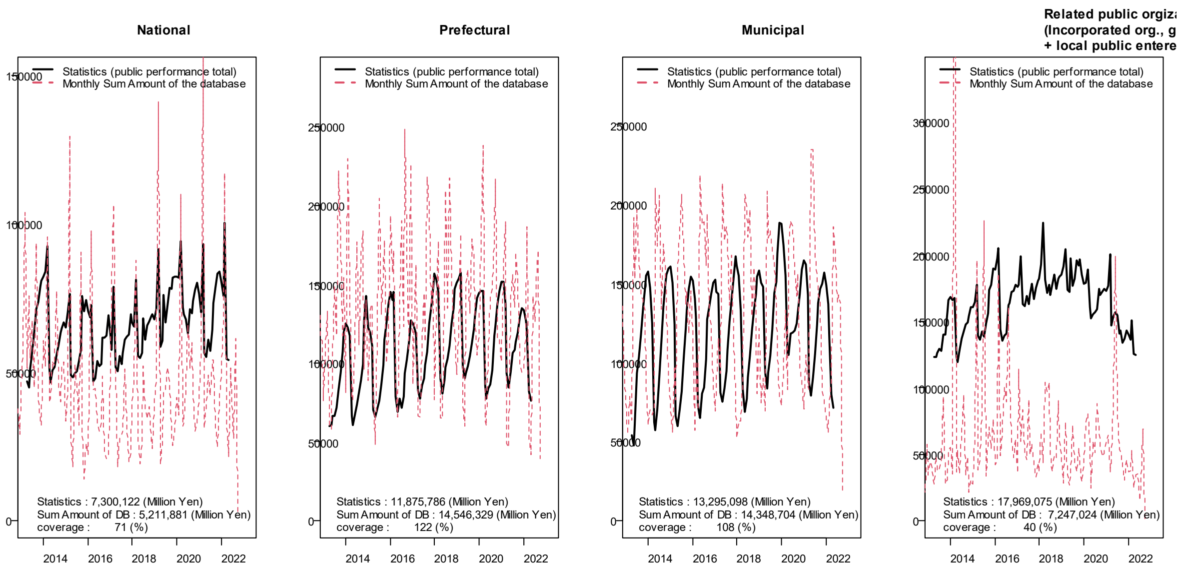


Fig. 2 Coverage of the database – compare with the Government's " General Construction Statistics": the amount figures in the public table (based on the amount of work completed) supervised by MLIT: Ministry of Land, Infrastructure, Transport and Tourism.

From whole databases, we created a subset of about 2.9 million construction-related projects, such as construction and civil engineering, whose bidding dates ranged from April 1994 to October 2022, and calculated the monthly total value of successful bids of them. These figures were tabulated according to four categories of public ordering agencies. (see red dashed lines in Fig.2) On the other hand, using the public sector table of the latest general construction statistics in eStat, we investigated the monthly "public performance total" in the Kanto region by public ordering agency, and obtained monthly values from April 2013 to May 2022. (black line in each figures). Fig. 2 compares these two amounts by public ordering agency. Overall, these figures show the high coverage of the database. In this study, analysis was performed using 142,672 data extracted from the database with 4 conditions mentioned above.

3. Over 20 years of competition system change

Examining the trends in the composition ratio of the number of projects over the last 20 years, we find that the construction type has changed from new construction to maintenance work in many public ordering organizations. Fig. 3 shows the various attributes of 142,672 data over 20 years.

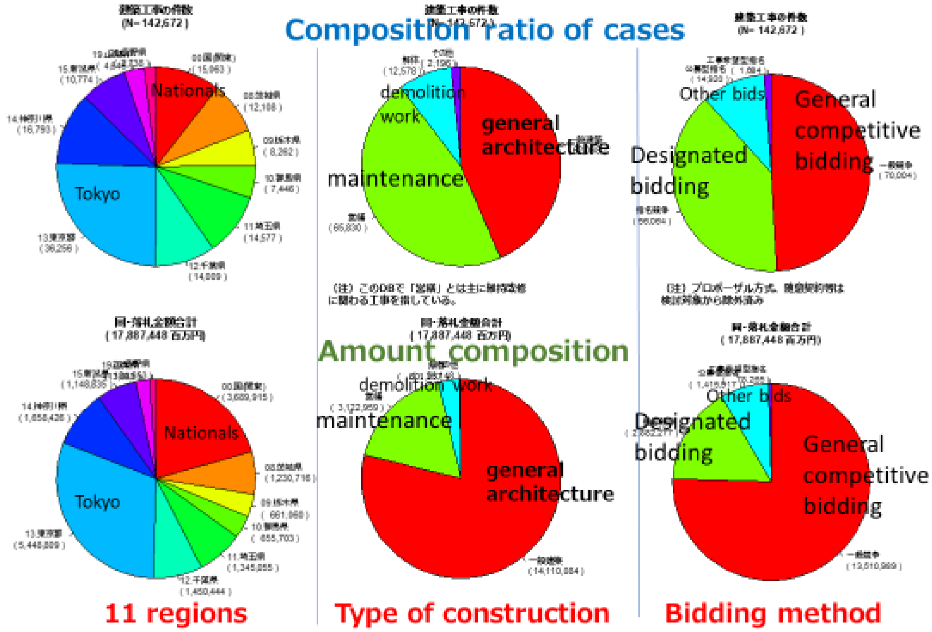


Fig. 3. Composition ratio of cases (upper side) and amount (lower side) of analyzed construction work data (All data looks like this: N=142,672; 17.8 trillion yen; and ranged fiscal year of 2001-2022).

In the case of MLIT (Ministry of Land, Infrastructure, Transport and Tourism) which is the main part of *the National* and which had taken the initiative for the reform, the bidding method changed significantly from 2005 to 2007. At that time, it had been gradually changed from designated competitive bidding to general competitive bidding. Such changes were expanded from large construction works to progressively smaller works. (see bold black line in Fig. 4).

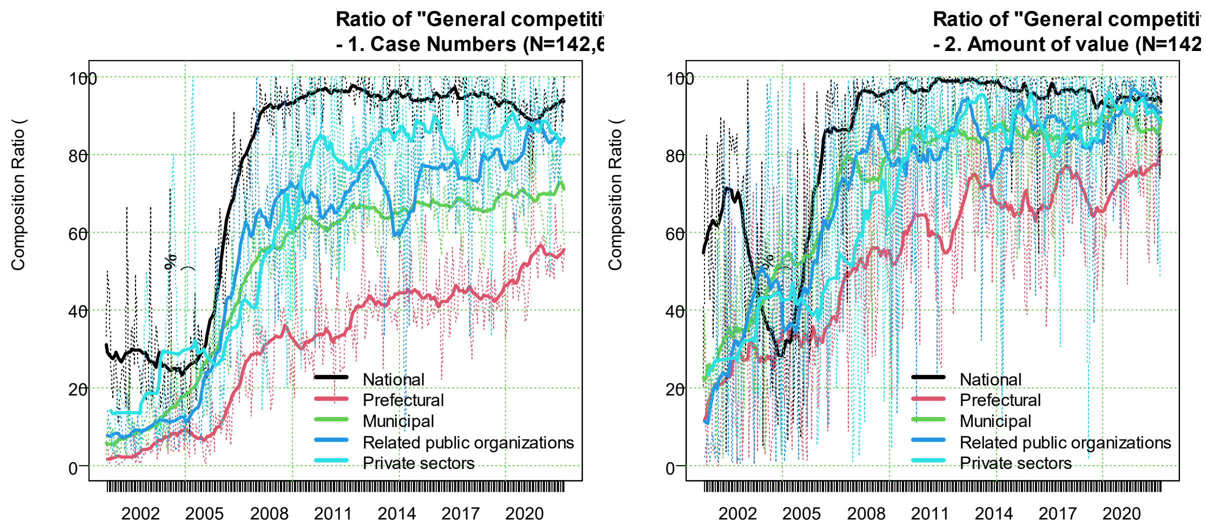


Fig. 4. Trends in monthly composition ratio (%) of bidding method classification "*General competitive bidding*" by ordering agency category with 12 months moving average: (left) composition ratio of cases, (right) composition ratio of sum amount

4. The number of bidders

The number of bidders has been gradually decreasing (see Fig.5). The number of bidders of general competitive bidding in *national* and *related public organizations* has bottomed out around 2007, and has declined sharply since December 2005, when private demand such as the housing mini-bubble by the second generation of baby boomers increased, and the construction industry leaders declared a farewell to bid rigging at that time. We remember that it was a period when the trend was remarkably competitive. During the period when designated competitive bidding was dominant, 10 nominations were common. This is probably because the Accounting Law had stipulated that "in a designated competitive bidding, at least 10 bidders must be nominated to participate in a competition". And it is true that similar measures had been taken all around Japan under the *Local Autonomy Law*.

The probability distribution of number of bidders had changed over time. Although there seems to be a difference in the distribution of number of bidders between the general competition and the designated competition over entire period, the difference due to bidding competition method is no longer clear for example in the probability distribution of the latest three years.

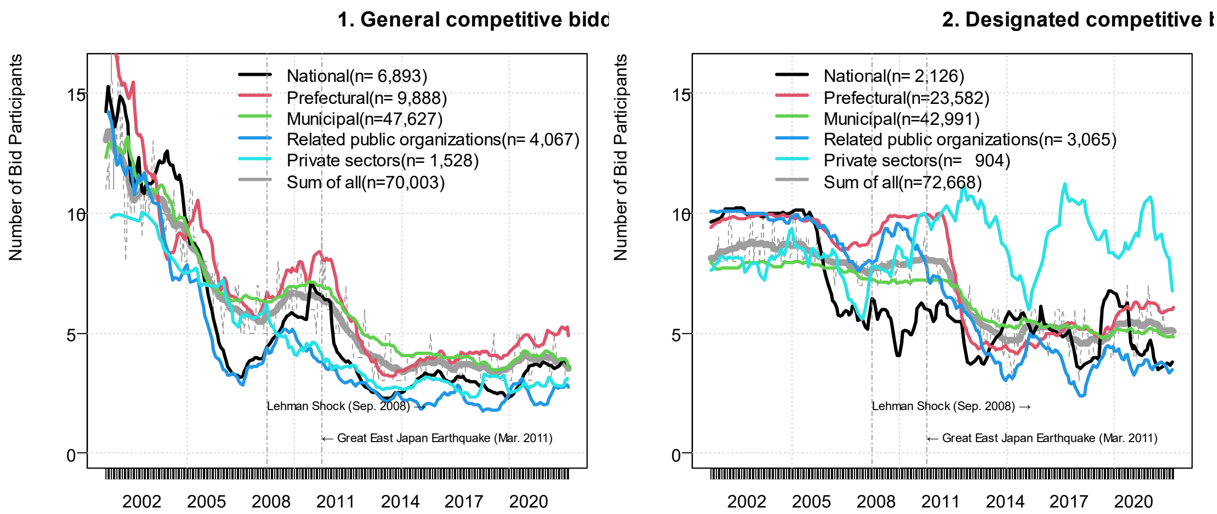


Fig. 5 Changes in number of bid participants --Differences between general competitive bidding and designated bidding.

4.1. Occurrence trends of "single bids"

As the number of bidders decreased, the single bids became more common. On February 13, 2014, three large construction projects related to the *Toyosu New Market* were ordered by the Tokyo Metropolitan Government (with successful bid amounts of approximately 24.7 to 41.5 billion yen), all of them were single bids won by JVs. In February of that year in Tokyo Metropolitan Government, a total of 134 bids all worth approximately 113 billion yen were all single bids. Later, under the newly elected governor of Tokyo, the reform of bidding system was tackled, and an attempt was made to cancel single bids in 2017 to 2018, but the impact on the implementation of public works projects was so great that the cancellation was abandoned. In addition, as regard the single bids, there is no written regulations of the JFTC (Japan Fair Trade Commission) regarding specific measures to be taken.

Fig. 6 shows the trends in the appearance rate of single bids calculated on a monthly basis by attribute of public ordering agencies. Since the monthly aggregated values vary when the number of cases is small, we calculated the 12-month moving average and indicated it with a thick line. The left side of the figure is based on the number of bids, and the right side is based on the successful bid price amount. When the latter number is higher than the former, it means that there were independent bids for relatively large-scale. Looking at these time-series charts, it can be seen that independent bidding became apparent after 2005. At that time, private construction projects such as condominiums were booming, and construction companies were extremely busy. However, after the collapse of Lehman Brothers in 2008, private construction demand plummeted, and interest in public works increased. Then, it became apparent again around 2014 after the Great East Japan Earthquake. During these period, the demand for post-earthquake reconstruction work had got into full-scale. In addition, with the Tokyo Olympic Games, the economy continues to improve, and private construction demand surpassed as if it were the bubble period in 1986-1991. And, there was a shortage of construction workers and construction costs soared.

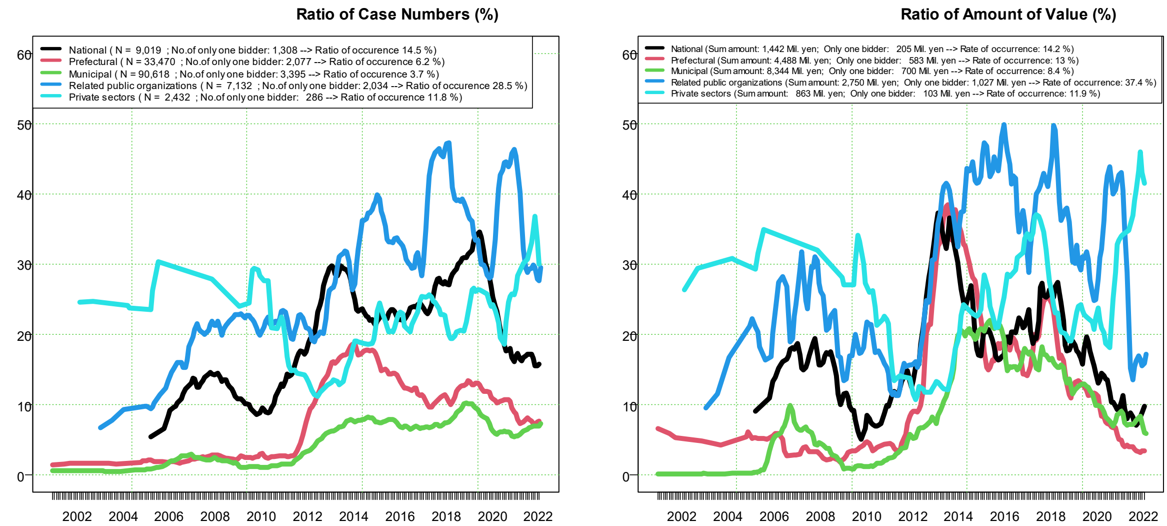


Fig. 6 Monthly occurrence of "single-bids" by ordering agency: (left) composition ratio of cases, (right) composition ratio of sum amount (12-month moving average; The number of single bids that occurred during the entire period, the total amount, and the ratio of each are shown in the legend column.).

4.2. How does the successful bid rate differ depending on whether it is a single bid or not?

The ratio of the successful bid price to the scheduled price determined in advance by the ordering agency is called the successful bid rate. It cannot be calculated if there is no scheduled price. In addition, there were more than 200 data without information on the number of bidders. Since 24,146 data in this database meet these conditions, it should be noted that the number of valid data will decrease especially in the private sector. The successful bid rate is often used as a proxy variable for judging the competitiveness of the bid, and cases with a high successful bid rate are often considered to be inferior in competitiveness. Fig. 7 compares the differences in successful bid rate distribution for the whole period by comparing whether it was a single bid or not. The median (thick black line in the square box) lies 95% of the time within a 'notch' of the statistical distribution error. In every figure, there is no overlap between the notch values of the box plots on the left end and those on the centre and right ends. In other words, although there are individual exceptions, overall the successful bid rate for single bids is high, and conversely, it can be said that single bids are less competitive. On the other hand, single bids generally have a high successful bid rate, but there is no clear difference between "Single bid as a result of withdrawal" and "Pure single bid from the beginning".

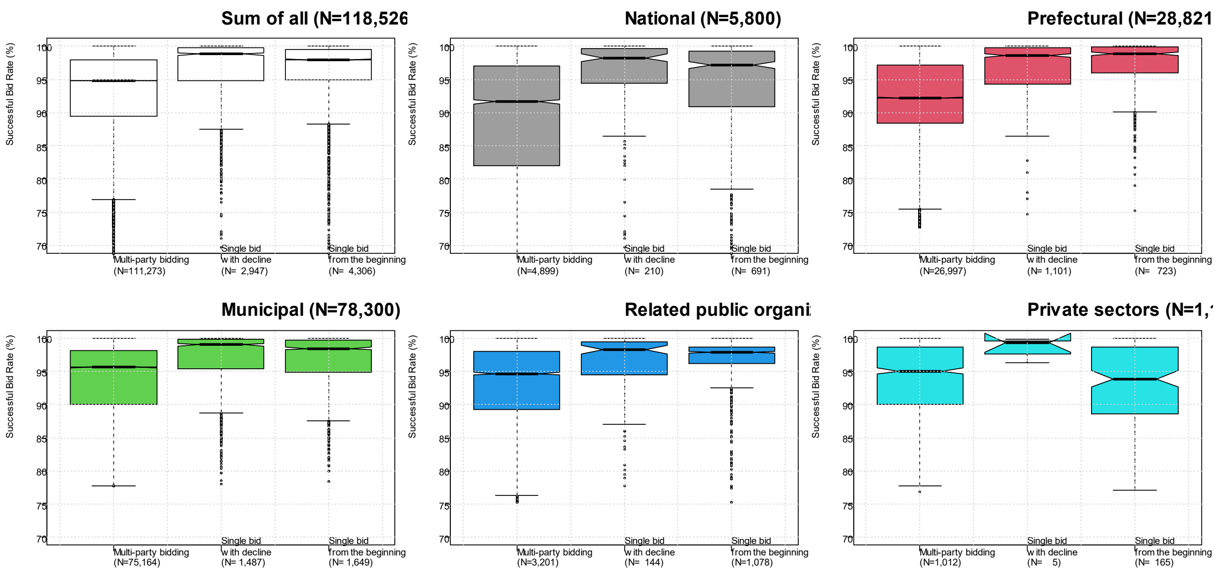


Fig. 7 Comparing successful bid rate over the entire period by whether or not it was a single bid (by public ordering agency) - -The data are divided into three parts: Multi-party bidding, Single bid as a result of withdrawal, and Pure single bid from the beginning.

5. Conclusions

The bidding result data collected by a construction newspaper company have revealed extremely high data coverage compared with the government statistics. A time series analysis was performed using these data. In recent years in Japanese construction tendering, the number of bidders has tended to decrease. In this survey, we were able to grasp the reality of single bids, which was not clear until now. The conclusions drawn in this study are summarized as follows:

- Over the last 20 years, the bidding system for construction work in Japan has changed significantly to general competitive bidding. And the number of participants in the tender gradually decreased. As a result, many single bids have been observed.
- Single bids has a higher successful bid rate than multiple bidding, and former cannot said to be tough competition compared with the latter by the analysis using successful bid rate metrics.

- In single bids, it cannot be said that the presence or absence of bid declines has any bearing on the successful bid rate.

References

[1] T. Akiyama, J. Iwamatsu and K. Endo. "Bidding Strategies in Japanese Construction Projects." CIB W55&W65 Joint Conference in Ohio Proceedings, Oct. 2002.

[2] J. Iwamatsu and K. Endo: A study on single-bid problem in some japanese public works marketplace: Alysis of public building works in the Kanto region from fy2001 to fy2021, (accessed 04.05.2023) (in Japanese) doi: 10.3130/aija.88.237

[3] J. Iwamatsu and K. Endo: Interpolation and Smoothing Methods of Building Unit Price Time Series Obtained from Building Starts Statistics, AIJ J. Technol. Des. Vol. 28, No.69, 982-985, Jun., 2022 (accessed 04.05.2023) (in Japanese) doi: 10.3130/aijt.28.982

[4] J. Iwamatsu and K. Endo: Impact of Number of Bidders on Japanese Construction Projects, Journal of Architecture and Planning (Transactions of AIJ), Vol.73, No.630, pp.1767-1773, 2008. (accessed 04.05.2023) (in Japanese) doi: 10.3130/aija.73.1767

[5] J.Iwamatsu, K. Endo and T. Akiyama "Japanese bidding patterns: a statistical approach." Construction Management and Economics 25th Anniversary Conference (CME25) Proceedings, 16-18th July 2007, University of Reading, UK, 12pages.

[6] J.Iwamatsu, K. Endo and T. Akiyama ”An analysis of transitional situations of bidding behavior by disclosed data”, Journal of Architecture and Planning, (Transactions of AIJ), No.622, pp.169-174, Dec. 2007. doi:10.3130/aija.72.169_2

[7] J.Iwamatsu, T. Akiyama and K. Endo,‘Bidding strategies in japanese construction projects: 2 Effect of enterprise scale on competitiveness’, Journal of Architecture and Planning, (Transactions of AIJ), No.565, pp.285-291, Mar. 2003,doi: 10.3130/aija.68.285

[8] J.Iwamatsu, T. Akiyama and K. Endo,”Bidding strategies in japanese construction projects: Bidding behavior that can be read from disclosed tender data”, Journal of Architecture and Planning (Transactions of AIJ), No.66, Vol.548, pp.207-213 (accessed 04.05.2023) doi: 10.3130/aija.66.207_4

[9] MLIT, Concerning the promotion of proper tendering and contracting for public works, (accessed 04.05.2023) https://www.mlit.go.jp/sogoseisaku/1_6_hf_000118.html

[10] MLIT, Tendering and Contracting System for Public Works, (accessed 04.05.2023) https://www.mlit.go.jp/sogoseisaku/1_6_hf_000078.html

AN OVERVIEW OF BREAKDOWN OF COMPETENCES IN MANAGING MAJOR CONSTRUCTION PROJECTS

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2 *Croatian Waters (Hrvatske vode), Zagreb, Croatia*

Abstract

Project manager's competences have become recognized as one of key project management actors in successful delivery of projects in today's world. This paper gives a literature overview of existing competence models, with a special accent on competences breakdown, the main components and its relationship, obtained through systematic literature review. Moreover, authors give an application of theoretical knowledge on those competences that matter the most in construction industry, which is traditionally oriented towards technical elements of project management, but exposed to numerous people and context factors. This makes major construction projects great example of demonstrating project manager's personality importance in successful project execution.

Peer-review under responsibility of the scientific committee of the Creative Construction Conference 2023.

Keywords: competence, construction, personality, project manager.

1. Introduction

Effective project management is crucial for successful project delivery [1]. Project managers play a vital role in managing project resources, schedules, budgets, risks, and stakeholders, to achieve project goals. However, the success of projects is not only determined by traditional, technical skills but also by project managers' competencies in managing project-related activities [2].

Competencies refer to a combination of knowledge, skills, attitudes, and behaviours that enable individuals to perform a job effectively [3]. Therefore, the competencies of project managers are critical in determining the success of projects. Several models of project management competencies have been developed to help organizations identify, assess, and develop the competencies of their project managers [4]. However, the breakdown of competencies in managing major construction projects is still an area that requires further exploration.

This paper aims to provide an overview of the breakdown of competencies in managing major construction projects, with a focus on the construction industry. The construction industry is unique in that it is exposed to numerous people and context factors, which can impact project success [5]. Therefore, major construction projects provide an excellent example of demonstrating the importance of project manager's competencies in successful project execution.

To achieve the aim of this paper, a systematic literature review was conducted. The review provides a comprehensive overview of existing literature on project management competencies, with a particular emphasis on the breakdown of competencies and their relationship. The authors will then apply theoretical knowledge on the competencies that matter the most in the construction industry.

This paper is structured as follows: the first section provides an introduction to the importance of project management and the significance of project managers' competencies. The second section reviews the existing literature on project management competencies, with a focus on the breakdown of competencies. The third section discusses the application of theoretical knowledge on project management competencies in the context of the construction industry. The final section provides concluding remarks and suggests areas for future research.

2. Literature review: PM competences breakdown

In order to make a systematic review on project management competences, databases (Science Direct, Google Scholar) were searched via key words: project management AND competence AND model OR breakdown. Only methodologies, standards and articles in English were examined. Authors analysed collected literature, and based on conducted research, an overview of different competence breakdown was made (Table 1). Some articles provided a detailed breakdown of competencies, while others simply provide an overview of the most important competencies for project managers. Only articles that present a specific set of competencies, were analysed.

Table 1. An overview of competencies breakdown in literature

Reference	Competence categories	Competences	Total number of competences
[3]	Practice	Project design; Requirements and objectives; Scope; Time; Organization and information; Quality; Finance; Resources; Procurement; Plan and control; Risk and opportunity; Stakeholders; Change and transformation	29
	People	Self-reflection and self-management; Personal integrity and reliability; Personal communication; Relationships and engagement; Leadership; Teamwork; Conflict and crisis; Resourcefulness; Negotiation; Results orientation	
	Perspective	Strategy; Governance, structures, and processes; Compliance, standards, and regulation; Power and interest; Culture and values	
[6]	Knowledge	Procedures; Instruments; Methods	14
	Performance	Initiating; Planning; Executing; Monitoring and control; Closing	
	Personal	Communicating; Leading; Managing; Cognitive ability; Effectiveness; Professionalism	
[7]	Setting up for success	Life cycles; Governance arrangements; Sustainability; Financial management; Business case; Portfolio shaping	29
	Preparing for change	Procurement; Reviews; Assurance; Capability development; Transition management; Benefits management	
	People and behaviors	Stakeholder engagement and communication management; Conflict resolution; Leadership; Team management; Diversity and inclusion; Ethics, compliance, and professionalism	
	Planning and managing deployment	Requirements management; Solutions development; Quality management; Integrated planning; Schedule management; Resource management; Resource capacity planning; Budgeting and cost control; Contract management; Risk and issue management; Change control	
[8]		Emotional Intelligence; Collaboration; Adaptability; Critical Thinking; Problem solving	5
[9]	Performance	Manage Stakeholder Relationships; Manage Development of the Plan for the Project; Manage Project Progress; Manage Product Acceptance; Manage Project Transitions; Evaluate and Improve Project Performance	6
[10]		Strategy and Project Management; Business planning, Lifecycle management, Reporting and Performance Measurement; Change and Journey; Innovation, Creativity and Working Smarter; Organizational Architecture; System thinking and Integration; Leadership; Culture and Being Human; Probity and governance	9
[11]	Technical		
	Leadership (based on [12])		
[12]	Emotional competencies	Motivation; Conscientiousness; Sensitivity; Influence; Self-awareness; Emotional resilience; Intuitiveness	15

	Managerial competencies	Managing resources; Engaging communication; Developing; Empowering; Achieving	
	Intellectual competencies	Strategic perspective; Vision and imagination; Critical analysis and judgement	
[13]	General management	Knowledge; Legal Skills; Communication; Social awareness; Action management; Financial Management	19
	Project Management	Integration; Report; Risk; Scope; Human resource; Procurement; Time; Quality; Cost	
	Project specific	Associated resume; Multiple project management; Technical skills; Availability for the project	
[14]		Organizational management capability; Integrated project management capability; Professional and technical capability; Construction site management capability; Experience and certification; Coordination and communication capability; External stakeholder management capability; Digital capability; Project team management capability	9
[15]	Core competency areas: General Management skills	Leadership; Negotiation; Communication; Team building	23
	Core competency areas: Project Management skills	Fundamental PM skills; PM tools and techniques; Organizational savvy	
	Core competency areas: Industry skills	Breadth (not depth) in specific application/industry knowledge Life cycle management	
	Personality: Characteristics	Aptitude, flexibility, and ability to adapt to change and cultural realities; Confidence and commitment; Pro-active, can-do attitude; Open mindedness; Common sense; Trustworthy; Creative	
	Personality: People management skills	Build and manage interpersonal relationships; Ability to influence and win respect; Know when NOT to manage; Politically sensitive; Active listening; Role model; Fairness	
[16]	Behavioral	Leadership; Communication; Emotional intelligence; Motivation; Influence; Dynamic; Creative; Flexibility; Ethical; Sensitivity	29
	Technical or specific	Product; Technical; Software; Industry; Engineering; Test	
	Management	Planning; Certification; Resource Management; Change Management; Monitoring; Negotiation; Risk Management	
	Contextual	Organization; Business; Relationship; Environment; Process; Marketing	
[17]	Practical competencies	People; Budget; Schedule	10
	Common Sense Competencies	Patience; Wisdom; Sense of humor; Flexibility; Creativity; Knowledge of the law of unintended consequences; Subject Matter Expertise	

Total number of 13 different PM competence breakdowns were analysed, and then synthesized into two main categories: hard and soft competence, which is an approach inspired by Crawford and Pollack [18].

3. Application of PM breakdown on construction projects

In order to make an application of competence breakdown on construction industry, especially infrastructure ones as the most complex, a breakdown based on Table 1 was given to group of experts. Focus group consisted of four project management professionals, all civil engineers, working on large infrastructure projects in water sector, with at least 8 years of working experience on them. Expert task was to determine which hard and which soft competences from the Table 1 were the most relevant one for managing the most critical risks occurring on infrastructure projects in water sector. If they wanted, they could add or rename a competence to fit on the best possible manner to they beliefs. The identification of most critical risks emerged from [19]. They represent risks in all phases of project lifecycle, defined as 54 risks across 11 categories. Based on risk assessment on portfolio of 60 water and wastewater EU co-financed infrastructure projects in Croatia, the most severe risks were identified. For them, results provided by the focus group are given in Table 2.

Table 2. Hard and soft competences crucial for managing most critical construction risks

Risk	Hard competence	Soft competence	Description
Epidemic / Pandemic	Crisis Management Resource Management	Leadership Communication	A project manager with crisis management skills will be able to respond effectively to the pandemic, while leadership, communication and resource organization skills are crucial for motivating and managing the project team through the uncertain and challenging times.
Insufficient quality and errors in project documentation	Quality Management Legal Knowledge	Communication	Quality management skills are necessary to ensure that project documentation meets the required standards, while communication skills are important for ensuring that all stakeholders understand the documentation requirements and processes.
Delay of public law bodies in the procedures for making other permits and decisions	Legal Knowledge	Negotiation	Legal skills are needed to navigate the complex legal and regulatory environment, while negotiation skills are necessary for managing relationships with public bodies and stakeholders.
Economic crisis	Financial Management Contract Management	Resilience	Financial and contract management skills are necessary to manage the project budget and finances during economic uncertainty, while resilience skills are needed to help the project team manage stress and stay focused on goals.
Change in prices of construction materials and services	Cost Estimation Contract Management	Flexibility	Cost estimation skills and contract management are necessary to manage project budgets and costs effectively, while flexibility skills are required to adjust the project plan or implement other resolution in response to changing market conditions.
Difficulty in securing funding sources	Financial Management	Communication Negotiation	Financial management skills are necessary for identifying funding sources and managing project finances, while communication is key to keep stakeholders informed of situation and process of securing funds.
Delay in preparation of procurement documentation	Procurement Time Management	Teamwork Communication	Procurement skills are necessary to manage the procurement process and ensure that documentation is completed accurately and on time, while time management skills are essential for meeting project timeline. Communication and teamwork is needed due to interdisciplinary and complexity of public procurement process.
Insufficient quality and errors in procurement documentation	Procurement Engineering and Technology	Attention to Detail	Procurement skills are necessary for managing the procurement process and knowledge on technics and technology ensures that documentation meets required standards, while attention to detail is important for ensuring that documentation is accurate and complete.
Delay in review and evaluation of bids	Procurement Time Management	Teamwork Communication	Procurement skills are necessary for managing the bid review and evaluation process, while time management skills are important for ensuring that the process is completed within the project timeline. Again, communication and teamwork is needed due to interdisciplinary and complexity of public procurement process.

Appeal in any part of the public procurement procedure	Legal Knowledge	Communication Coordination	Legal knowledge is necessary for understanding the appeal process and ensuring that the project complies with legal requirements, while coordination skills are required for managing relationships with stakeholders involved in the appeal.
Lack of Contractor's manpower	Resource Management	Team Building	Resource management skills are necessary for managing project resources, while team building skills are required for building a strong project team and ensuring that the team is motivated and focused on project goals.
Unresolved property-legal relations	Legal Knowledge	Problem Solving Negotiation	Legal knowledge is necessary for resolving property and legal issues, while problem-solving and negotiation skills are required for identifying and addressing any underlying issues that may be contributing to the unresolved issues.
Archaeological or conservation requirements and conditions, or sites	Environmental Management	Cultural Awareness	Environmental management skills are necessary for managing the project in compliance with environmental regulations, while cultural awareness skills are important for understanding and managing the project in culturally sensitive areas.
Unfavorable field conditions	Site Assessment	Adaptability	Site assessment skills are necessary for understanding and assessing the risks associated with unfavorable field conditions, while adaptability skills are required for adjusting the project plan to address these risks.

Based on these insights, a construction based critical PM competence breakdown for infrastructure projects in water sector was made and given on Figure 1.

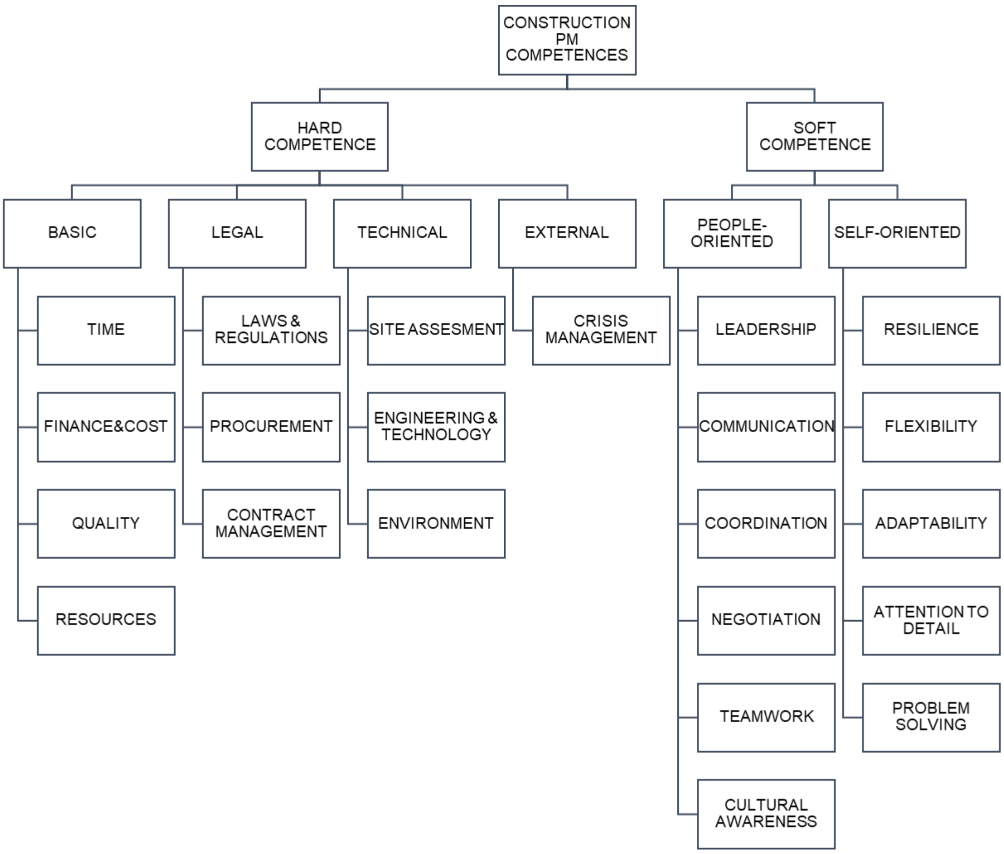

Figure 1. Construction PM competences breakdown for infrastructure projects in water sector

As it can be seen from Figure 1, there is a huge importance on so called soft competences, oriented on relations with people and self. Traditional technical knowledge on PM will always be a backbone to any successful PM attempt, but soft skills become if note more, than at least equally as important as time or budget management. This is of special importance on major construction projects, which by the definition are more complex not only in terms of budgets, scopes and timespan, but in number of stakeholders to manage, organizational and external changes and impacts – which are again designed from people – for people. Managing people not only within the team, but in broader sense of all interested formal and informal project parties becomes a crucial element in project success formula.

4. Discussion and conclusion

Effective project management is one of the most critical factors for overall project delivery success, mostly depending on competences of project manager. There are many different approaches for categorisation and identification of PM competences in general, but not as many in identifying specific competences for different types of projects or contexts. In this article authors gave suggestion of construction PM competence breakdown made upon the most critical risks on major infrastructure projects, which show great value of soft PM skills, both self- and people-oriented.

Based on Figure 1, hard technical competence such as time, budget, scope, and quality management play an important role both in literature review and its application on water infrastructure projects. Competences such as procurement and contract management, and knowledge of applicable laws and regulations were emphasized on the portfolio because of many important legislations that shape the governance of those projects. Out of literature competences, creativity was not as important, because those projects are managed in accordance with strict predefined procedures. Out of competences dealing with people focus group stressed out communication and negation as extremely important competence in coordination of different stakeholders and situations.

The results of this research are important because by building critical competence breakdown, PMs can focus on education and advancement of those competence that matter the most, which is especially the case in soft skills, that one does not learn in school.

Limitations of this study lay in fact that the breakdown is proposed by employment of focus group method, and not verified by adoption of quantitative methodology on large sample. Also, it is made only for one type of construction projects. On the other hand, these results indicate possible way for future research on the field.

Future research should aim at broadening suggested approach for different types of construction projects and in depth investigation of importance of PM soft skills on them.

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References

[1] Z. Alias, E. M. A. Zawawi, K. Yusof, and N. M. Aris, “Determining Critical Success Factors of Project Management Practice: A Conceptual Framework,” Procedia - Social and Behavioral Sciences, vol. 153, pp. 61–69, 2014, doi: 10.1016/j.sbspro.2014.10.041.
[2] B.-G. Hwang and W. J. Ng, “Project management knowledge and skills for green construction: Overcoming challenges,” International Journal of Project Management, vol. 31, no. 2, pp. 272–284, Feb. 2013, doi: 10.1016/j.ijproman.2012.05.004.
[3] International Project Management Association, "IPMA Competence Baseline, Version 4.0.," 2015.
[4] L. Crawford, “Senior management perceptions of project management competence,” International Journal of Project Management, vol. 23, no. 1, pp. 7–16, 2005, doi: 10.1016/j.ijproman.2004.06.005.
[5] W. Soon Han, A. Md Yusof, S. Ismail, and N. Choon Aun, “Reviewing the Notions of Construction Project Success,” International Journal of Business and Management, vol. 7, no. 1, 2011, doi: 10.5539/ijbm.v7n1p90.
[6] Project Management Institute, “Project Manager Competency Development Framework – Second Edition”, 2007.
[7] Association for Project Management, “APM Competence Framework – Third Edition”, 2023.
[8] UK government, “PRINCE 2 Methodology”, 2017.

[9] Global Alliance for Project Performance Standards, “A Framework for Performance Based Competency Standards for Global Level 1 and 2 Project Managers”, 2007.
[10] International Centre for Complex Project Management (ICCPM), “Complex Project Manager Competency Standards, Version 4.1.”, 2012.
[11] R. Müller and J. R. Turner, “Matching the project manager’s leadership style to project type,” International Journal of Project Management, vol. 25, no. 1, pp. 21–32, 2007, doi: 10.1016/j.ijproman.2006.04.003.
[12] V. Dulewic and, M.J. Higgs, “Design of a new instrument to assess leadership dimensions and styles,” Henley Working Paper Series HWP 0311. Henley-on-Thames, UK: Henley Management College; 2003.
[13] M. Sadatrasool, A. Bozorgi-Amiri, and A. Yousefi-Babadi, “Project manager selection based on project manager competency model: PCA–MCDM Ap-proach,” Journal of Project Management, no. 10, pp. 7–20, 2016, doi: 10.5267/j.jpm.2017.1.004.
[14] H. Liu, H. Zhang, R. Zhang, H. Jiang, and Q. Ju, “Competence Model of Construction Project Manager in the Digital Era—The Case from China,” Buildings, vol. 12, no. 9, p. 1385, 2022, doi: 10.3390/buildings12091385.
[15] N. Udo and S. Koppensteiner, “What are the core competencies of a successful project manager?”, PMI® Global Congress 2004—EMEA, Prague, Czech Republic. Newtown Square, PA: Project Management Institute, 2004.
[16] S. Sajedi and M.A. Shirazi, “Critical Competencies in Project-Based Organizations: An Interpretive Structural Modelling approach”, Proceedings of the International Conference on Industrial Engineering and Operations Management Pilsen, Czech Republic, July 23-26, 2019.
[17] W. Turk, “21st Century Project Management Competencies”, Defense AT&L, no. January-February, 2007.
[18] L. Crawford and J. Pollack, “Hard and soft projects: a framework for analysis,” International Journal of Project Management, vol. 22, no. 8, pp. 645–653, 2004, doi: 10.1016/j.ijproman.2004.04.004.
[19] M. Sjekavica Klepo, D. Knezevic, T. Knezevic, and H. Mestrovic, “Artificial intelligence in risk management system on infrastrcture projects“, Creative Construction Coonference 2023, (submitted for publication).

ARTIFICIAL INTELLIGENCE IN RISK MANAGEMENT SYSTEM ON INFRASTRUCTURE PROJECTS

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Abstract
Infrastructure projects are crucial elements of the way we perceive the world we live in – they are pillars of economy and society development. In order for them to be carriers of change, they are ought to fulfil their goals successfully. With the rise of complexity of project endeavours, uncertainty to accomplish them successfully rises, too. Therefore, risk management, with the aim to identify, analyse, respond, monitor and control potential unfavourable events on projects, has an even more important role in complex environment such as infrastructure projects are. In order to contribute to todays' state-of-the-art risk management dealing with infrastructure projects, but also to identify the most crucial risks and the way project managers could deal with them, this research was conducted. Research sample consisted of EU co-financed infrastructure projects portfolio in water sector. First, risks were identified and analysed by project managers. Then, the most critical risks and response strategies were identified for the whole portfolio. Afterwards, artificial intelligence was also engaged in order to formulate adequate risk response strategies. Both PM expert and AI strategies were overlapped, and adequate conclusions were made, in order to contribute to more efficient implementation of risk management procedures on projects.

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Keywords: artificial intelligence, FIDIC, infrastructure, project management, risk.

1. Introduction

There is no doubt we live in a project world nowadays - it is estimated that around $18,3 trillion is spent on projects worldwide every year [1]. Projects are pillars of change, but in order for those changes to be implemented, project endeavours must be successful. This is stressed on a special manner if we speak about infrastructure projects, which are key drivers of economic growth and social development, critical for reducing poverty, improving health and education outcomes, and achieving environmental sustainability [2]. This means there is much more to manage then the traditional iron triangle of cost, time and quality, therefore, they require much wider, holistic approach to project management [3]. As a fundamental part of project management, risk management is emphasized especially through this holistic approach. Risk management, as an insurance that potential issues and uncertainties are identified and addressed in a proactive and strategic manner [4], is essential for the successful implementation of infrastructure projects [5].

In year 2020, it was stated that new possibilities arise in managing risks on construction projects with the implementation of artificial intelligence (AI) by helping project managers (PM) to identify potential risks more quickly and accurately, and to develop more effective risk response strategies [6]. Nevertheless, while AI holds promise as a tool for managing risks in construction projects, more research is needed to fully understand its potential and limitations [7].

With this being stated, authors decided to conduct research which will contribute to the state-of-the-art on AI potentials in risk management on the example of water infrastructure projects. The portfolio consisted of 60 EU co-financed infrastructure projects dealing with drinking water and wastewater infrastructure in Croatia.

Firstly, a review of relevant literature on the field of infrastructure risk management and AI in risk management was made. Then, an applicable risk matrix model created for water infrastructure projects, presented in the Appendix A, was used to collect data on the most significant risks on the portfolio. In the second part of the article, methods and results of conducted research are shown, consisting of identification of most critical risks and applicable response strategies delivered by PMs and an open-source AI. Results are discussed and final remarks, as well as recommendations for the future studies are given in the conclusion.

2. Literature review

Risk management involves identifying potential risks, assessing their likelihood and impact, developing response strategies, and monitoring and controlling risks throughout the project lifecycle. In recent years, there has been growing interest in the use of AI for risk management in construction projects, which was highlighted by several studies. For example, Chen et al. highlight the potential of AI to transform risk management practices in the construction industry [6]. Similarly, Zhang et al. note that AI can be an effective tool for identifying, analysing, and managing risks on construction projects, leveraging large volumes of data and advanced analytics to improve decision-making and enhance project outcomes [7]. According to the findings [8], the management of cost, schedule, and risk, in particular, will be highly affected by AI. This is not surprising because registering and analysing historical information to estimate how long will it take to finish future tasks, as well as the associated costs and risks might become a slow and tricky task for PMs, so the automation by combining an AI-based solution with project management software will be extremely helpful [9]. However, there are also challenges and limitations associated with the use of AI for risk management in construction projects. Data quality issues, model interpretability, and the need for specialized technical expertise are among the key challenges that need to be addressed [7]. Also, there is an importance of considering human factors in risk management, noting that AI should be used as a complementary tool rather than a substitute for human judgement [10]. Despite these challenges, there is growing interest in the potential of AI for risk management in construction projects, as well as in other industries such as IT [11] or project management as general [12, 13], with some areas to explore [14].

Based on literature review, it is visible that future research in this area should focus on addressing the challenges and limitations associated with the use of AI for risk management, as well as on developing practical tools and techniques for integrating AI into existing risk management practices.

3. Methods and results

This research was conducted on portfolio of 60 water and wastewater EU co-financed infrastructure projects in Croatia, which by the nature are very sensitive to risks materialization. To ensure effective and efficient project implementation, eleven characteristic risk categories and fifty four unique risks presented in the Appendix A were identified. Grants Beneficiaries (water-utility companies) within portfolio mostly use FIDIC Red (for water and sewage networks) and Yellow Book (for wastewater or sludge treatment plants) contracts. The risk analysis was conducted by PMs appointed by the Intermediate Body of Level 2, via MS Excel file [15]. All gathered data was summarized for analysis and distinguished by FIDIC Red or Yellow book classification. Risks were assessed as materialized (if they had already occurred) or probable (if not). Within these two main categories, risks were evaluated by PMs assessment of impact that they gave/could give to a project, reflected by the intensity gradient ranging from “Low” to “Moderate”, “Significant”, “High”, and “Severe”. By combining the probability of an event occurring with its potential impact as a one-step exercise, the efforts towards investigating more suitable theories and approaches that appeal to practitioners and reflect their experience and practice was utilized [16]. After completing matrixes for all risks, PMs filled in additional information about response strategies they employed to manage those risks. After completing data gathering, analysis was conducted following these methodological steps:

1. Top 20% of the most frequent risks assessed as “Severe” were calculated for entire portfolio (Table 1). This was made by employment of Pareto 80/20 rule, which suggests that 80% of the project's risks may stem from 20% of the identified risks. Therefore, PMs can focus their efforts on the top 20% of the critical risks to effectively manage the project's overall risk profile [17]. The frequency of occurrence is marked as f (%), and risks are marked as given in Appendix A.
2. Risk response strategies were qualitatively analysed and transformed into general notes on possible behaviours in accordance to the most critical risks (Table 2).
3. As the last step, AI was prompted to generate risk response strategies. As a part of this step, authors used open source AI, ChatGPT [18]. The comparison between results from step 2 and step 3 are given in Table 2.

Table 1. The most critical severe risks on portfolio

RED FIDIC BOOK				YELLOW FIDIC BOOK			
MATERIALIZED		POSSIBLE		MATERIALIZED		POSSIBLE	
RISK	***f (%)***	**RISK**	***f (%)***	**RISK**	***f (%)***	**RISK**	***f (%)***
R.8.1	8,54%	R.2.3	18,00%	R.1.3	11,81%	R.2.3	15,22%
R.4.3	7,54%	R.2.4	17,50%	R.6.5	9,03%	R.2.4	15,22%
R.7.1	5,53%						
/	21,61%	/	35,50%	/	20,84%	/	30,44%

The most critical possible risks for both FIDIC book contracts were shown to be R.2.3. and R.2.4., which in case of EU co-financed projects are interlinked risks on special manner, due to the lack of clear guidelines on eligibility of extra project expenses on the one hand, and the need to adopt to this situation regarding the current market state and fulfilment of contracts goals on the other hand. The most critical materialized risks detected on Red FIDIC book contracts were R.8.1., R.4.3. and R.7.1. Risk R.8.1. reflects recent state of construction labour market in Croatia, where there has been severe emigration of local manpower to other EU countries along with strictly defined insufficient worker import quotas. R.4.3. caused serious delays in project progress due to COVID restrictions of work and large number of sick leaves and quarantines in period 2020-2022. Risk R.7.1. is stressed on the special manner in Red FIDIC contracts, where the Employer is responsible for design documents, so all of latent design errors cause delays and extra costs in construction phase. Yellow FIDIC Book specifics were R.1.3. and R.6.5. Analogous to R.7.1. in Red FIDIC contracts, R.1.3. is quite often in Yellow FIDIC contracts, because obtaining construction permits is the responsibility of the Contractor, who often lacks control over the processes of other public entities, i.e. bodies responsible for issuing permits, which usually leads to extension of total contracted time. R.6.5. is common on public projects as a part of public procurement procedure, which can cause several-month delay in contracting. On Yellow FIDIC Book contracts this is especially the case due to higher average time needed to finalize design and build contracts in comparison to Red FIDIC Book contracts. For critical elaborated risks, risk response strategies given by PMs and AI are given in Table 2.

Table 2. Risk response strategies for the most critical severe risks on portfolio (strategies marked in matching colors within one risk category are PM-AI overlapping)

<table>
<tr><th rowspan="3">RISK</th><th colspan="4">RISK RESPONSE STRATEGY</th></tr>
<tr><th colspan="3">PM</th><th>AI</th></tr>
<tr><th>STRATEGY</th><th>CATEGORY</th><th>f (%)</th><th>STRATEGY</th></tr>
<tr><td rowspan="5">RF,
M,
R.8.1</td><td>Subcontractors contracting</td><td>SHARING</td><td>36,36</td><td rowspan="5">Working with alternative subcontractors or suppliers
Reassigning tasks to other personnel
Adjusting project timelines
Increasing incentives for existing workers</td></tr>
<tr><td>Introduction of multiple work groups/shifts</td><td>MITIGATION</td><td>27,27</td></tr>
<tr><td>Intensive recruitment advertising</td><td>MITIGATION</td><td>18,18</td></tr>
<tr><td>Pressure on the contractor to acquire additional labor force</td><td>MITIGATION</td><td>9,09</td></tr>
<tr><td>Dynamic plan revision</td><td>MITIGATION</td><td>9,09</td></tr>
<tr><td rowspan="3">RF,
M,
R.4.3</td><td>Compliance with prescribed COVID measures</td><td>ACCEPTANCE</td><td>62,50</td><td rowspan="3">Implement health and safety protocols and measures
Remote work</td></tr>
<tr><td>On-line coordination and meetings</td><td>MITIGATION</td><td>25,00</td></tr>
<tr><td>Extension of contracted period</td><td>MITIGATION</td><td>12,50</td></tr>
<tr><td>RF,
M,
R.7.1</td><td>Additional changes in project/design documentation</td><td>MITIGATION</td><td>100,00</td><td>Correction of project/design documentation
Thorough review of project documentation
Implement quality management systems (e.g. software tools or dedicated personnel to manage project documentation)</td></tr>
<tr><td rowspan="4">RF,
P,
R.2.3</td><td>Government motivating Employers to consider possibilities for adopting price differences within contractual provisions</td><td>SHARING</td><td>79,16</td><td rowspan="4">Monitor market conditions due to procurement requirements
Negotiating fixed-price contracts (the Contractor takes on the risk of any cost increases)
Seeking alternative suppliers
Re-evaluating project requirements</td></tr>
<tr><td>Revision of planned procurement values for new contracts</td><td>AVOIDANCE</td><td>8,33</td></tr>
<tr><td>Contractors storing larger amounts of required materials</td><td>MITIGATION</td><td>8,33</td></tr>
<tr><td>Cancelling public procurement procedure</td><td>AVOIDANCE</td><td>4,18</td></tr>
<tr><td rowspan="2">RF,
P,
R.2.4</td><td>Increase of co-financing rates by the non-EU co-financiers</td><td>TRANSFERENCE/ SHARING</td><td>71,43</td><td rowspan="2">Seek alternative funding sources such as grants or private investors</td></tr>
<tr><td>Phasing a project/ enabling financing from other operational programs</td><td>TRANSFERENCE</td><td>28,57</td></tr>
<tr><td rowspan="3">YF,
M,
R.1.3</td><td>Extension of contracted period</td><td>MITIGATION</td><td>72,72</td><td rowspan="3">Maintain regular communication with public law bodies to ensure that any issues or delays are identified and addressed in a timely manner and to expedite the decision-making process</td></tr>
<tr><td>Reminders to public authorities to consider faster permits issuing</td><td>MITIGATION</td><td>18,18</td></tr>
<tr><td>Idea on prioritizing permits issuing for strategic / EU co-financed projects</td><td>TRANSFERENCE</td><td>9,09</td></tr>
<tr><td rowspan="3">YF,
M,
R.6.5</td><td>Increase in quality and clarity of tender documentation</td><td>AVOIDANCE</td><td>33,33</td><td rowspan="3">Ensure clear and well-defined evaluation criteria and the objective selection of bidders
Ensure compliance with procurement regulations and guidelines to minimize the risk of appeals (e.g. involve engaging legal advisors or procurement specialists to advise)</td></tr>
<tr><td>Idea on prioritizing appeals solving for strategic / EU co-financed projects</td><td>TRANSFERENCE</td><td>33,33</td></tr>
<tr><td>Phasing a project/ enabling financing from other operational programs</td><td>TRANSFERENCE</td><td>33,33</td></tr>
<tr><td>YF,
P,
R.2.3</td><td>Government motivating Employers to consider possibilities for adopting price differences within contractual provisions</td><td>SHARING</td><td>60,00</td><td>Monitor market conditions due to procurement requirements</td></tr>
</table>

	Contractors storing larger amounts of required materials and equipment	MITIGATION	40,00	Negotiating fixed-price contracts (the Contractor takes on the risk of any cost increases) Seeking alternative suppliers Reevaluating project requirements
YF, P, R.2.4	Increase of co-financing rates by the non-EU co-financiers	TRANSFERENCE/ SHARING	100,00	Seek alternative funding sources such as grants or private investors

A priori prompting AI for risk responses, it was “trained” to context of project management and risk management on legislative framework governing EU co-financed projects, and current state construction market in Croatia. Based on this setup, AI was prompted with list of the most critical severe risks (Table 1) and gave corresponding risk response strategies (Table 2) resulting with 21 different strategies. There is an overlapping of 52% in strategies between PM and AI in suggested actions, mostly among the most frequent occurring strategies. Among the “AI generated” strategies, one strategy is not as applicable to EU co-financed projects: Re-evaluating project requirements. Namely, project requirements are derived from project scopes, which are identified in project preparation phase, and verified through different steps (feasibility study, design documents, project application). Shrinking requirements to fit the new price would possibly lead to unfulfillment of designed project indicators and goals, which is extremely sensitive on EU co-financed projects and may lead to financial corrections. Among strategies that could be of added value, implementation of quality management system in accordance to verification of design documents prior to execution on field can be of extreme value. These systems could implicate standardisation of works and bill of quantities or implementation of BIM as a part of organizational strategy. Also, taking advice of legal experts in public procurement procedures could really lead to minimization of appeals in public procurement procedures. The most critical risk on both of FIDIC books contracts is definitely change in prices of construction materials and services. AI suggested to implement fixed price contracts which would shift all of the risks in price change to Contractor. Nevertheless, most of the PMs suggested more flexible approach in sharing that risk between Employer and Contractor in accordance to contract provisions and positive regulations and recommendations in specific national context. Namely, according to national law, even in the case of contracted fixed prices, the Contractor has the right for reimbursement of the price difference if it increases by more than a certain percentage, so it is never possible to completely transfer the risk of price change on the Contractor. Transferring this risk on Contractor solely would mean higher price of works a priori, which in case of normal market conditions would not be favourable to the Employer or EU budget. Moreover, it would put the Contractor to the risk of insufficient cash flow on the project, affect the works dynamics, and may ultimately result in the termination of the contract and legal disputes.

To conclude, AI did gave some additional good and thought worthy strategies to consider, but human endeavour is needed in assessment of suitability and implementation of them within the given context.

4. Conclusion

Effective risk management is essential for the success of construction infrastructure projects. In this work, an overlapping of human and artificial intelligence was made in accordance to risk response strategies of the most critical severe risks on water infrastructure projects.

While the use of AI for risk management in construction projects is a relatively new and rapidly evolving area, it holds promise as a tool for improving project outcomes, especially after the introduction of Open source AI, such as the one used in this research. However, more research is needed to fully reveal the potential and limitations of AI for risk management in construction projects, and to develop practical tools and techniques for integrating AI into existing risk management practices, e.g. broadening presented methodology on other infrastructure sectors. A lot of future research will be depended on the course of AI development both in general and specific directions, such as AI specialized for different PM areas.

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Appendix A. Risk matrix

SOURCE OF RISK	RISK CATEGORY	RISKS
EXTERNAL	1. POLITICAL	R.1.1. Changes in legal regulations (building regulations, public procurement, other laws and regulations) R.1.2. Elections - local, national R.1.3. Delay of public law bodies in the procedures for making other permits and decisions
	2. FINANCIAL AND ECONOMY	R.2.1. Economic crisis R.2.2. Insufficient availability of potential contractors R.2.3. Change in prices of construction materials and services R.2.4. Difficulty in securing funding sources
	3. SOCIAL	R.3.1. Negative attitude of the local community towards the project R.3.2. Insufficient support from the local management structure
	4. ENVIRONMENT AND NATURE	R.4.1. Natural disasters (earthquakes, floods, fires) R.4.2. Unfavourable climatic conditions R.4.3. Epidemic / Pandemic
INTERNAL	5. MANAGEMENT AND ORGANIZATION	R.5.1. Lack of support from top management R.5.2. Inadequate human resources involved in project management R.5.3. Insufficient coordination and communication within the team and on the entire project
	6. PUBLIC PROCUREMENT	R.6.1. Inadequate human resources involved in the preparation and implementation of the public procurement procedure R.6.2. Delay in preparation of procurement documentation R.6.3. Insufficient quality and errors in procurement documentation R.6.4. Delay in review and evaluation of bids R.6.5. Appeal in any part of the public procurement procedure R.6.6. Administrative dispute
	7. DESIGN	R.7.1. Insufficient quality and errors in project documentation R.7.2. Delay in delivery of project documentation R.7.3. Delay in the approval of project documentation by the Employer
	8. PEOPLE AND LOGISTICS	R.8.1. Lack of Contractor's manpower R.8.2. Accidents and incidents at the construction site R.8.3. Unavailability of necessary equipment for work R.8.4. Unavailability of materials and equipment to be installed
	9. CONTRACT AND LEGAL	R.9.1. Delay in concluding a contract after a successful public procurement procedure R.9.2. Ignorance of contractual provisions R.9.3. Poor management of contractual documentation by the Contractor R.9.4. Poor change management R.9.5. Unrealistically short deadlines for the implementation of works R.9.6. Errors in the contract documentation / poor quality of the contract R.9.7. Poor organization and management of contractors R.9.8. Insufficient construction communication and coordination between contracting parties R.9.9. Insufficient presence of stakeholders in contract management (Supervision, Contractor, subcontractors) R.9.10. Delay in resolving Contractor's claims and resolving contractual disputes prior to escalation R.9.11. Delay in making necessary decisions
	10. CONSTRUCTION SITE AND CONSTRUCTION	R.10.1. Unresolved property-legal relations R.10.2. Inadequate and imprecise dynamic work execution plan R.10.3. The planned implementation technology does not correspond to the actual situation on the site R.10.4. Wrong staking out of the object and inconsistency with the cadastral plan R.10.5. Problems in granting the right of access to the construction site, difficult access to the construction site R.10.6. Insufficient coordination or delay in obtaining consent and closing certain streets for the purpose of carrying out works R.10.7. Finding protected habitats and species at the location of the works R.10.8. The amount of work significantly deviates from the contracted amount R.10.9. Inexperience and incompetence of contractors, subcontractors or suppliers
	11. PHYSICAL CONDITIONS	R.11.1. Unexpected geological and geotechnical soil characteristics R.11.2. Archaeological or conservation requirements and conditions, or sites R.11.3. Groundwater level higher than predicted / expected R.11.4. Physical obstacles in the corridor of works R.11.5. Environmental pollution R.11.6. Unfavourable field conditions

References

[1] Project Management Institute, Pulse of the Profession® 2021: A Global Survey of Project Professionals, 2021, retrieved from https://www.pmi.org/-/media/pmi/documents/public/pdf/learning/thought-leadership/pulse/pulse-of-the-profession-2021.pdf (Access date: 1.6.2022)

[2] R. Osei-Kyei and A. P. C. Chan, "Review of studies on the Critical Success Factors for Public–Private Partnership (PPP) projects from 1990 to 2013," International Journal of Project Management, vol. 33, no. 6, pp. 1335–1346, 2015, doi: 10.1016/j.ijproman.2015.02.008.

[3] B. Flyvbjerg, "What you Should Know about Megaprojects and Why: An Overview," Project Management Journal, vol. 45, no. 2, pp. 6–19, 2014, doi: 10.1002/pmj.21409.

[4] J. K. Pinto and D. P. Slevin, "Critical Success Factors Across the Project Life Cycle: Definitions and Measurement Techniques," Project Management Journal, vol. 18, no. 1, pp. 5-18, 1987, doi: 10.1177/875697288701800104.

[5] F. Khosrowshahi and Y. Arayici, "Managing Risks in Infrastructure Projects: A Case Study of the Dubai Metro," Journal of Infrastructure Systems, vol. 18, no. 2, pp. 120-130, 2012, doi: 10.1061/(asce)is.1943-555x.0000088.

[6] Y. Chen, H. Li, S. Li, Y. Li, and C. Wang, "Artificial Intelligence for Risk Management in Construction Projects: A Review," Journal of Construction Engineering and Management, vol. 146, no. 2, pp. 04019118, 2020, doi: 10.1061/(asce)co.1943-7862.0001762.

[7] Y. Zhang, Q. Shi, H. Li, and Y. Lu, "Artificial Intelligence for Risk Management in Construction: Opportunities and Challenges," Automation in Construction, no. 124, pp. 103602, 2021, doi: 10.1016/j.autcon.2021.103602.

[8] T. V. Fridgeirsson, H. T. Ingason, H. I. Jonasson, and H. Jonsdottir, "An Authoritative Study on the Near Future Effect of Artificial Intelligence on Project Management Knowledge Areas," Sustainability, vol. 13, no. 4, p. 2345, 2021, doi: 10.3390/su13042345.

[9] C. J. Pampliega, "Inteligencia artificial en el sector de la construcción= Artificial inteligence in construction sector," Building & Management, vol. 3, no. 2, pp. 1-5, 2019.

[10] A. J. Al-Bayati, M. F. Mohd Yusof, and Z. Mustafa, "The role of human factors in the implementation of artificial intelligence in construction risk management," International Journal of Construction Management, vol. 19, no. 3, pp. 219-230, 2019, doi: 10.1080/15623599.2018.1472291.

[11] M. El Khatib and A. Al Falasi, "Effects of Artificial Intelligence on Decision Making in Project Management," American Journal of Industrial and Business Management, vol. 11, no. 03, pp. 251–260, 2021, doi: 10.4236/ajibm.2021.113016.

[12] M. Munir, "How artificial intelligence can help project managers," Global Journal of Management And Business Research, vol. 19, no. 4, pp. 29-35, 2019.

[13] J. Gil, J. Martínez Torres and R. González-Crespo, "The Application of Artificial Intelligence in Project Management Research: A Review," International Journal of Interactive Multimedia and Artificial Intelligence, vol. 6, no. 6, p. 54, 2021, doi: 10.9781/ijimai.2020.12.003.

[14] S. Bento, L. Pereira, R. Gonçalves, Á. Dias, R. L. d, and a Costa, "Artificial intelligence in project management: systematic literature review," International Journal of Technology Intelligence and Planning, vol. 13, no. 2, p. 143, 2022, doi: 10.1504/ijtip.2022.126841.

[15] Microsoft Corporation, Microsoft Excel (Version 2016) [Computer software], Redmond, WA: Microsoft Corporation.

[16] A. Taroun, "Towards a better modelling and assessment of construction risk: Insights from a literature review," International Journal of Project Management, vol. 32, no. 1, pp. 101–115, 2014, doi: 10.1016/j.ijproman.2013.03.004.

[17] J. Oehmen, B. Dick, U. Lindemann, and W. Seering, "Risk management in product development–current methods," InDS 36: Proceedings DESIGN 2006, the 9th International Design Conference, 2006.

[18] OpenAI GPT-3.5 Language Model, 2021, retrived from https://openai.com/blog/gpt-3-5b-model-release/ (Access date: 31.3.2023)

BALANCING PRIVATE INVESTMENT AND COMMUNITY EXPECTATIONS IN PUBLIC-PRIVATE-PARTNERSHIP PROJECTS: A NOVEL APPROACH FOR EVALUATING LONG-TERM VALUE

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Abstract

Balancing private investment and community expectations is always crucial in social Public-private-Partnership (PPP) projects, such as schools, public housing, and hospitals. Evaluating the value of such PPPs requires the governments to accurately assess costs, risks, and benefits through their Public Sector Comparator (PSC). The Public Sector Comparator (PSC) focuses on the economic benefits and tangible value offered by bidders, such as whole-of-life financing costs, capital costs, operation, maintenance costs, and risk allocation as proposed by the government. Non-monetized benefits, which are vital during the delivery of social infrastructure, are typically evaluated heuristically by comparing specific solutions proposed by bidders. However, assessing uncertainties in government requirements and materialized risks when comparing a bid to Public Sector Comparator (PSC) using discounted cost techniques at a specific point in time is challenging. Therefore, this paper proposes a novel approach for evaluating investments that considers non-monetary benefits over a PPP project's life cycle, based on the risks and benefits seen in recent social PPP projects. Engineering reliability analysis is preferred in this study to emphasize the performance reliability of investment decisions. The proposed reliability-based evaluation considers not only cost uncertainty and non-monetary benefits based on project observations but allows for time-based decision-making by being used at multiple points in time, to be incorporated into the original investment decision. Future case study is expected to demonstrate that the proposed approach allows for predicting long-term value by using a performance reliability index to measure the robustness of the original investment assumptions such as demand projections and future sustainability outcomes.

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Keywords: investment evaluation, non-monetary benefits, PPP, reliability, social infrastructure.

1. Introduction

Over the years, public-private-partnership (PPP) projects are increasingly used around the world in delivering infrastructure or building services for governments in mitigating financial burdens [1]–[3]. According to the latest statistical data from [4], private investment commitments totalled $76.2 billion in 2021 in the low- and middle-income countries, representing a 49% increase from 2020 due to economic recovery from COVID-19. As a particular procurement approach, PPPs bundle investment and service provision of infrastructure into a single long-term contract [5]. On the one hand, the developed policies and legal structures within PPP arrangements assist the involvement of the private sector [6], on the other hand, the governments have found 'value for money' in using a PPP approach for many infrastructure projects through an availability model of payment [7]–[9]. The 'Value for Money' is often reported as a comparison of the bid prices received versus public sector comparator estimates, which has been a key objective of government to achieve the optimal combination of benefits and costs in delivering services users 'wants' [10]. However, the efficient and effective evaluation of such 'Value for Money' for PPPs investment has always been one of the points of major debates across governments and researchers.

[11]–[13] have criticized that Ineffective investment evaluation accounts for one of the reasons leading to the difficulties experienced in PPPs. There are examples where the private sector party has been dissatisfied [14], where poor long-term demand forecasts have resulted in facilities struggling to meet the expectations due to overcrowding, such as Southern Cross Station in Australia [15]. Currently, the investment evaluation of PPPs relies heavily on government's pre-estimate of how much the project would cost, if traditionally delivered, using government funds [16]. This whole of life risk adjusted estimate of the provision of the service is termed as the Public Sector Comparator (PSC), which is a point estimate and therefore struggles to consider variances that occur over the commission period, usually 25 or 30 years, to the delivered performance. In addition, often the PSC emphasizes economic evaluation of value for money and is challenged to adequately or fully incorporate non-monetary benefits [17], [18]. While the real value of PPPs for government, particularly social infrastructure projects, i.e., schools, hospitals, and public housing, is judged by what the community experience rather than a point in time estimate used in the tender evaluation process [19]. Though some sought to consider changing assumptions with time using real option evaluation techniques, but this approach is also very dependent on the underpinning model assumptions [20], [21].

Considering PPPs, particular social PPPs, always need to balance the advantage of private investment against community expectations [19] during the government governs and controls the services provided over the long term. This study aims to explore the merits of considering the social PPP investment decision using a reliability-based approach that incorporates costs and non-monetary benefit profiles quantification, and stochastic risk impact over a project's life cycle. The proposed approach, firstly, contributes to the existing research of social PPP investment evaluation through measuring the non-monetary benefits from the perspective of community expectation. Next, the advantages of engineering reliability analysis were adopted to quantify the uncertainties in costs and non-monetary benefits over the whole project life cycle. Thus, this evaluation of the merits of the project in terms of costs and non-monetary benefits, could serve as a template for investment decision-making process in future similar PPP projects.

This remaining content is organized as follows. Section 2 presents an extensive overview of relevant PPP investment evaluation literature. Section 3 develops the reliability-based evaluation approach. Conclusions are given in section 4.

2. Literature Review

2.1 PPP and PFI

The concept of PPP, also refers to 3P or P3, is underpinned by the governments desire to resolve financial constraints in the provision of public infrastructure and services by calling upon private management skills to increase the efficiency, effectiveness and quality of infrastructure and services delivery [22]. Although there is no uniform definition of PPP, it is generally accepted that it refers to a long-term arrangement between one or more public and private sector for the delivery of services and infrastructure [23]–[25]. It developed not only because of a need for increased investment in public infrastructure, but also as a method of improving service delivery by the public sector without having to resort to privatization or the need for increased public funding as it is structured on a project finance basis [26]. Compared with the conventional procurements, it is advantageous that it allows a long-term, output-based arrangement with risks being allocated to the party best placed to bear them, and the aim of minimizing cost overruns and delays by using private sector expertise, thereby achieving value for money [27]–[29]. Notably, the level of private sector involvement might range from service provision without recourse to public infrastructure based on public infrastructure usage, up to and including full private ownership of public facilities an operation of their associated services[30]. For example, within the typical PPPs in Australia, i.e., Design-Build-Finance-Operate-Maintain (DBFOM), the private sector is responsible for the design, build/construction, finance, operation or maintenance of the infrastructure assets and services, usually over a period of 25 to 30 years. In a similar way, The UK government has identified eight forms of PPPs, the most used one of which is the Private Finance Initiative (PFI)[29]. The key difference between PPP and PFI is the way of financing [26]. That is, PFI utilizes debt and equity finance provided by the private sector to pay for the upfront capital costs, but the same is not required in a PPP, where the parties have more freedom to structure their contributions. Depending on this structure, PPP can therefore include public sector finance. A further difference is that a PPP may be structured as a joint venture or through contract, a PFI will make use of a special purpose vehicle (SPV) that will not only enter contractual arrangements with the relevant public sector entity, but also enter the financing arrangements with its shareholders and external financiers. As a result, it should be noted that while all PFIs will be PPPs, not all PPPs are PFIs. Though PFI was the very first term adopted by the British government, nowadays, PPP has become more popular and most used worldwide [31].

In this study, the focus will be put on the social PPPs, which refer to procuring the community services and resources such as health, education, early-childhood care, community support and development, culture, sport, recreation, and parks in PPPs that aim to support liveability of communities in meeting their social needs and wellbeing [32]. Compared to the other PPPs, like transport PPPs, social PPPs are more related to social benefit rather than revenues or profits.

2.2 Current PPP investment evaluation approaches review

The investment evaluation approaches drawn from existing literature could be broadly categorized into two categories, i.e., quantitative evaluation and qualitative evaluation, see Table 1. Quantitative evaluation involves analyzing the financial data, such as cash flows, revenues, costs, and profits, associated with an investment opportunity in various projects. The investment indicators based on these financial data analyses have been widely adopted including Internal rate of return [33], [34]; payback period [35], [36]; benefit cost ratios [37]–[39] and net present value [40]. For example, [41] justified the use of internal rate of return method to evaluate the PPP investment evaluation under a proposition. [42], [43] developed the net present value model to facilitate the decision-making of determining the PPP concession period. [39] built a base of cost benefit analysis for a PPP airport project in India. In spite of these traditional quantitative evaluation in PPP projects, value for money (VFM), which refers to delivering improved public infrastructure or services at lower cost, has been proposed to evaluate particular PPP projects with the common characteristics [44]. The structure of VFM also contains a quantitative component, called public sector comparator (PSC) that measures to what extent the cost saving can be achieved when delivering through PPP compared to traditional public-sector procurement approach [45]. The PSC is a baseline of risk-adjusted life-cycle cost to delivering public infrastructure using traditional procurement method[46], including base costs, transferred risk, retained risk by government and competitive neutrality[47]. Lots of researchers [48]–[53] and governments [54], [55] have focused on the use and improvements of VFM in PPP projects.

Table 1 Investment evaluation approaches

Categories	Investment indicators	References
Quantitative	Cash flows; payback period; benefit cost ratios; internal rate of return; net present value	[33]–[35], [38]–[41], [56]–[61]
Qualitative	Performance evaluation; qualitative comparative analysis	[14], [62]–[66]
Both quantitative and qualitative	Value for Money	[7], [8], [10], [46], [51], [54], [55], [67]

While considering social PPPs are more related to social benefit rather than revenues or profits, the qualitative approaches are thus developed. For example, [62] explored the utilisation of qualitative comparative analysis in facilitating the complexity-informed evaluation for PPP projects. In earlier years, [68] integrated qualitative and quantitative risk analysis for investment in PPP projects in Indonesia. Some qualitative performance evaluation work can also revoke the social benefits thinking of PPPs. For example, [63] evaluated the operational flexibility and innovation into the benefits of PPP school projects. [11], [64], [66] proposed a process-based evaluation framework for PPP projects, which strategically places an emphasis on value for money to improve the effective of performance. Notably, VFM considerations include not only PSC but also a qualitative reflection of other factors, such as policy support, quality of service, delivery speed and macroeconomic conditions etc [67]. More examples of research that has considered quantifying qualitative elements in investment decisions include: the work by [13] who identified the linkages between a PPPs financial and commercial structure with the quality of services received in power stations, or the work of [69]who developed a qualitative evaluation system of VFM using analytic hierarchy process. Real option-based approaches have been developed as an approach to maximize VFM but validation of these approaches is still required [70], [71]. However, The weight carried by these qualitative factors in the actual investment decision appears to vary considerably and there is no definitive guidance on how these factors should be considered. Some use weighted attributes others appear to use judgement. An ongoing concern in the use of VFM is that decision makers primarily rely on the financial analysis, and may inappropriately discount other social benefits and costs that don't impact directly on the facility being examined [45].

2.3 Research Gap

Many of the inherent benefits in social PPP projects are non-monetary and evaluation of these factors involves significant uncertainty. When considering commercial investments, traditional quantitative analyses include consideration of systematic risks in the discount rate, and this is frequently sufficient to compare one project to another. In social infrastructure PPPs, the specific project risks and benefits are explicitly considered and thus the assumption regarding these risks requires particular attention [72]. Further, it is unpractical for PPPs to obtain accurate cash-flow data to achieve such evaluations, because of great uncertainty involved not only construction of the infrastructure, but often its long-term operation and maintenance in PPP infrastructure projects. The qualitative evaluation could make up the deficits of above financial methods by shedding light on considering the non-monetary benefits. However, it is difficult to provide an intuitive determination when making investment decisions for future similar social PPP projects. Mostly importantly, the quantitative and qualitative evaluations are based on single point estimates of costs and benefits taken at a particular time. Consequently, this kind of approach ignores potential fundamental changes over project's life cycle time.

The proposed evaluation approach for future social PPP investment are advantageous at clarification of cost uncertainty and quantification of observed benefits. The indicator of performance reliability, which is described as the probability of failure, of a project that does not meet it's expected outcomes [19] is employed via engineering reliability analysis to calculate the impact of cost and benefit changes over a project life cycle. It can be used as an investment index for the future similar projects. Though[73] proposed to use this approach to focus on reliability and economics for infrastructure projects, There is limited specific research into the any enhanced benefits for social infrastructure investment procured under a PPP arrangement. These qualitative aspects include the quality of service delivered, the level to which community expectations are met and depth to which the sustainability development goals of [74] need to be considered. It is expected to act as a potential managerial tool for governments to make logical decisions on social projects investment that more fully considers sustainability outcomes.

3. Reliability-based Investment Evaluation Approach

3.1 Quantifying Project Life Cycle Cost

Industry accepts the basis of using cost-benefit analysis, and governments often use a benefit to cost ration as an important criterion to select favorable investment [75]. [58] applied cost-benefit analysis as a part of project sustainability assessment, which indicates cost performance as an important consideration for achieving sustainable projects. The approach being developed in this study extends cost benefits analysis to the specifics of social PPPs, and then to incorporate uncertainty that may vary with time via engineering reliability analysis.

In considering costs associated with social PPPs, the featured payment mechanism is considered where the total cost is initially financed by 'Project Co' and then repaid by government during project concession period (generally via quarterly service payments), normally between 25 and 30 years. It is worth mentioning that total cost of social PPPs can be composed of construction costs, finance cost, operation cost and whole of life maintenance and refurbishment cost. In the development of quantifying cost performance in this approach, operational costs are defined to include all ongoing costs, e.g., maintenance cost, rehabilitation cost, cleaning cost, etc. From the perspective of contract, the total payments made by government are the summation of the quarterly service payment (QSP) through the whole concession period, (refer eqn 1).

$$TC_{gov,T} = \sum_{t=1}^{T} \frac{QSP_{gov,t}}{(1+i)^T} \tag{1}$$

Where i is the discount rate. T means the term of the concession period.

Over the long term life of a social PPP, there will invariably be the need for changes or additional services, the direct impact on cost performance of such changes remains a concern for both the public and private sector [76]. Minor changes are often envisaged in the original contract and these specific changes are dealt with via either preidentified projects or through mechanisms to undertake minor works. Price adjustments to the payment regime follow the contract. From time to time there may be a requirement for a major modification to the agreement. These modifications are not generally envisaged by the contract, but a clear mechanism is included in the contract through which price and scope adjustments can be determined. Cost adjustments associated minor works changes are reflected in the model by (C_{mw}) and modifications are reflected by (C_m). Should "Project Co" not deliver the contracted services to an agreed standard, government may abate part of the quarterly payment, termed C_a. Therefore, the actual sum paid,i.e., C_{qsp}, is based on an adjusted cost base. The actual cost to government (AC) and total cost (ATC) considering the cost uncertainty at the year t and T can be represented as detailed in eqns 2 and 3.

$$AC_{gov,t} = \frac{C_{qsp,t} + \sum_{m=1}^{M_t} C_{mw,m,t} + \sum_{n=1}^{N_t} C_{m,n,t}}{(1+i)^t} \tag{2}$$

$$ATC_{gov,T} = \frac{\sum_{t=1}^{T} C_{qsp,t} + \sum_{t=1}^{T}\sum_{m=1}^{M_t} C_{mw,m,t} + \sum_{t=1}^{T}\sum_{n=1}^{N_t} C_{m,n,t}}{(1+i)^T} \tag{3}$$

The index has been illustrated in the Table 2.

Table 2. Index Description

Index	Explanations	Values
$ATC_{gov,T}$	The actual total cost borne by the government at the year T	Provided by Equation (3)
$C_{qsp,t}$	The cost of quarterly service payment (C_{qsp}) at the year t	Historical data, predicted using time-series algorithm in MATLAB
$C_{mw,m,t}$	The cost of minor works (C_{mw}) due to government for the m_{th} time at the year t	Historical data, predicted as normal distribution variable
$C_{m,n,t}$	The cost of modifications (C_{mr}) due to government for the n_{th} time at the year t	Historical data, predicted as normal distribution variable
$QSP_{gov,t}$	The planned quarterly service payment (QSP_{gov}) in the contract	Historical data in the contract
$TC_{gov,T}$	The total cost borne by the government specified in the contract at the year T	Historical data in the contract
i	Discount rate, indicating the value of time in the investment evaluation process	2.85%, usually in the project summary report
m_t	Total times of minor works at the year t	Historical data, predicted as random variable
n_t	Total times of modifications at the year t	Historical data, predicted as random variable
T	The length of concession period	Usually, 25 or 30 years

Typically, the cost performance of infrastructure project is often in the form of cost growth, i.e. the percentage difference between the final contract amount and the contract award amount [77], [78], thus for social PFIs, cost performance can be expressed as:

$$c_t(\%) = \frac{AC_{gov,t}}{QSP_{gov,t}} \tag{4}$$

$$c_T(\%) = \frac{ATC_{gov,T}}{TC_{gov,T}} \tag{5}$$

A further cost performance assessment normalization is conducted to unitize cost and non-monetary benefits in social PPPs. In this study, a scale from 1 to 7 are used to replace the measurement of c_t, in which the cost overrun of -20%, 0%, 20% respectively representing the score of 1, 4 and 7, as illustrated in **Fig 1**. The higher scores, the worse cost performance.

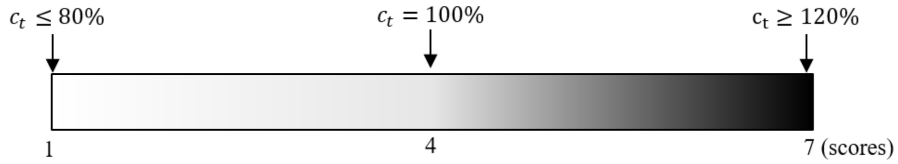

Fig 1. Cost Performance Assessment Normalization in Social PPPs

3.2 Quantifying Observed Benefits

Quantifying non-monetary benefits is the key point in the investment evaluation process of social PPPs, particularly for the decision-making of government. In this study, the quantifying of non-monetary benefits could provide a trade-off against the cost in social PPPs. However, the literature reviews show the benefit derived from social PPPs is complicated to capture also has not been valued in comparation with cost. In order to establish the benefit model in social PPPs, multi-criteria analysis, which has already been used in performance assessment of healthcare [79]transport projects [80] and sustainable water supply [81] is employed in this part to evaluate observed benefits. Multi-criteria analysis enables to evaluate what extent that the project satisfies performance criteria and thus has been the popular method for comprehensive assessment of economic, social and environmental benefits [58]. Here, a further improvement to combine multi-criteria analysis with analytic hierarchy process (AHP) [82] is adopted to quantify the observed non-monetary benefits of social PPPs, considering what and how the social infrastructure delivered is more highlighted than economic benefits. This part will shed light on the quantification of project benefit from two perspectives in [74], i.e., delivery of service and attracting and retaining the public. Three detailed steps are introduced for application in following process of framework test.

3.2.1 Identifying benefit categories derived from social PPPs

The identification of social PPPs benefit categories is a fundamental step for the quantification of non-monetary benefit in the reliability-based investment evaluation approach. Unfortunately, full benefit profile for social PPPs is difficult to obtain from literature. Under these circumstances, the adaptation of assessment indicators used in PPP sustainability from [83], [84] along with an in-depth expert interview, may be the best approach for this step. The benefit categories and its sub-items are listed in Table 3.

Table 3. Benefit Categories for Social PFIs

Benefit Categories	Sub-items
Delivery of service (DoS)	DoS_1: performance of output specifications in terms of DoS DoS_2: performance of operations and cleaning activities in terms of DoS DoS_3: performance of maintenance activities in terms of DoS
Attracting and retaining the Public ($ARtP$)	$ARtP_1$: performance of output specifications in terms of $ARtP$ $ARtP_2$: performance of operations and cleaning activities in terms of $ARtP$ $ARtP_3$: performance of maintenance activities in terms of $ARtP$

3.2.2 Allocating weights of benefit categories through AHP

Observed benefit of social PPPs can be expressed as:

$$B_{gov,t} = w_{DoS} \sum_{i}^{3} w_i \cdot DoS_i + w_{ARtP} \sum_{j}^{3} w_j \cdot ARtP_j \tag{6}$$

$B_{gov,t}$ represents observed benefit for government at the year t; w_{DoS} and w_{ARtP} are assumed equally in this research, thus 50% for each other; w_i, w_j $(i, j = 1,2,3)$ mean the weight sub-items of DoS_i and $ARtP_j$ by using AHP method, which is popular in multi-criteria analysis [85]. The AHP procedure is simply showed here: After identifying benefit categories and sub-items in the first step, a target-evaluation level, including respective DoS_i and $ARtP_j$, is set up to figure out the pairwise comparison matrix A by comparing their importance to each benefit categories, thus DoS and $ARtP$. For example, the element a_{ij} in A represents the importance of the ith element compared to the jth element. To get a_{ij}, the opinions of experts are collected using 1-9 rating scale, i.e., 1,3,5,7,9, where 1 represent equal importance, 9 represent extreme importance. In usual, an element receiving higher rating is viewed as superior compared to another one.

$$A = \begin{bmatrix} a_{11} & \cdots & a_{1j} \\ \vdots & \ddots & \vdots \\ a_{i1} & \cdots & a_{ij} \end{bmatrix} \tag{7}$$

a_{ij} complies with the following rules: $a_{ij} = 1,3, \ldots 9 \; or \; 1, 1/3, \ldots, 1/9$, $a_{ij} = 1/a_{ji}$, and $a_{ii} = 1$ for i and j.

Once the pairwise comparison matrix A is created, the normalized pairwise comparison matrix A_n is derived through making the sum of the entries on each column equal to 1, i.e.:

$$\bar{a}_{ij} = \frac{a_{ij}}{\sum_{i=1}^{m} a_{ij}} \tag{8}$$

m is the number of elements in the evaluation level, here $m = 3$; the weight of each element is computed by averaging the elements on each row of A_n:

$$w_i = \frac{\sum_{j=1}^{n} \bar{a}_{ij}}{m} \tag{9}$$

3.2.3 Measuring observed benefits of social PPPs.

The last step is data collection based on the non-monetary benefit categories. Using questionnaire in the 1-7 score Likert scale in accordance to the cost measurement, can get measurement matrix S. As shown in fig 2, the higher score is, the better benefit it achieves. It is worth mentioning that the normalization scale (1-7) is aimed for the normalization of comparison between cost and benefit.

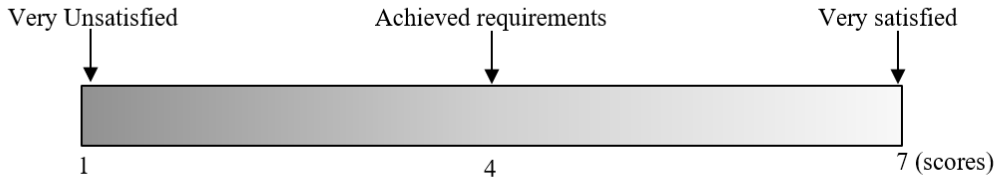

Fig 2. Observed Benefit Assessment Normalization

Finally, a general score representing how the benefit is achieved is derived by multiplying $\boldsymbol{S}$ and $\boldsymbol{W}$, i.e.,

$$B_{gov,t} = w_{DoS} \sum_{i}^{3} w_i \cdot DoS_i + w_{ARtP} \sum_{j}^{3} w_j \cdot ARtP_j = \boldsymbol{W} \cdot \boldsymbol{S} \tag{10}$$

The detailed process for the benefit quantification is illustrated as the Fig 3.

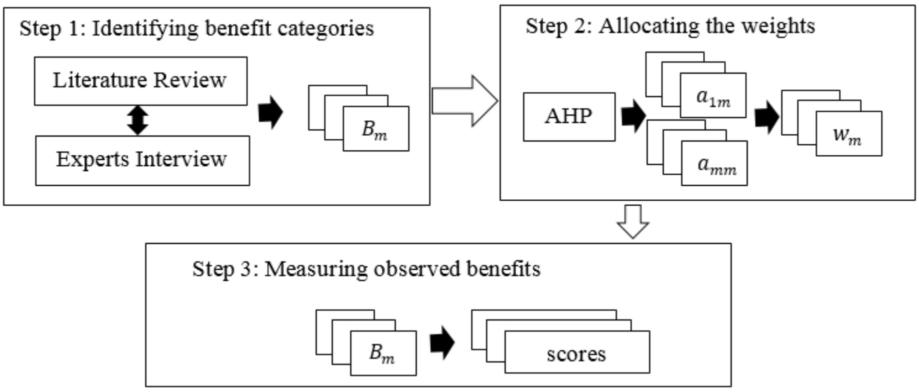

Fig 3. Observed Benefits Assessment Process in Social PPPs

3.3 Reliability Evaluation for Social PPP investment

Based on reliability analysis, the probability of failure ($P_{f,t}$) is figured out by eqn 11 [73]:

$$P_{f,t} = P(NPV < 0) = \int_0^\infty F_{B,t}(t) f_{C,t}(t) dt \tag{11}$$

Where $F_{B,t}(t)$ is the cumulative distribution function of observed benefits, $f_{C,t}(t)$ is the density distribution function of cost at time t, NPV here meaning the quantified observed benefits over cost. Cost and observed benefit variables are assumed as normally distributed for simplicity, in which $\mu_{C,t}$ and $\mu_{B,t}$ are the mean value of cost and benefit variables, $\sigma_{C,t}$ and $\sigma_{B,t}$ are standard deviation depending on uncertainty, then the probability of failure ($P_{f,t}$) represented by $\mathrm{NPV} < 0$, can be expressed as:

$$P_{f,t} = P(NPV < 0) = \emptyset\left[\frac{\mu_{C,t} - \mu_{B,t}}{\sqrt{\sigma_{B,t}^2 + \sigma_{C,t}^2}}\right] \tag{12}$$

Where Ø is the cumulative distribution function of the standard normal variable; $P_{f,t}$ is dependent on the ratio between the mean and standard deviation of variable NPV, which is called reliability index:

$$\text{Reliability index}(\theta_t) = \frac{\mu_{B,t} - \mu_{C,t}}{\sqrt{\sigma_{B,t}^2 + \sigma_{C,t}^2}} \tag{13}$$

Hence,

$$P_{f,t} = P(NPV < 0) = \emptyset[-\theta] = 1 - \emptyset(\theta) \tag{14}$$

When the data of cost and observed benefit is available at year t, the time-dependent probability of failure $P_{f,t}$ for social PPP investment could be calculated.

In summary, engineering reliability analysis is used to evaluate social PPPs investment through quantifying cost and observed non-monetary benefits, which aims to incorporate project uncertainty and explore how the service delivered by private sector under PPP mechanism. The reliability-based evaluation approach, inclusing six steps, is presented in Fig 4.

Step 1: Identifying social PPPs research context.

Step 2: Establishing life-cycle cost and non-monetary benefit model within PPP payment mechanism and benefit quantification process.

Step 3: Collecting data for the input variables in cost and benefit model.

Step 4: Normalizing cost and non-monetary benefits variables within 1-7 scales, in case of preciseness and applicability of following engineering reliability analysis.

Step 5: Engineering reliability analysis is employed to explore uncertainty impact on social PPP investment, the result of which is in the form of probability of failure $P_{f,t}$ and reliability index (θ_t).

Step 6: Providing practical recommendations for decision-makers regarding further similar social PPP investment.

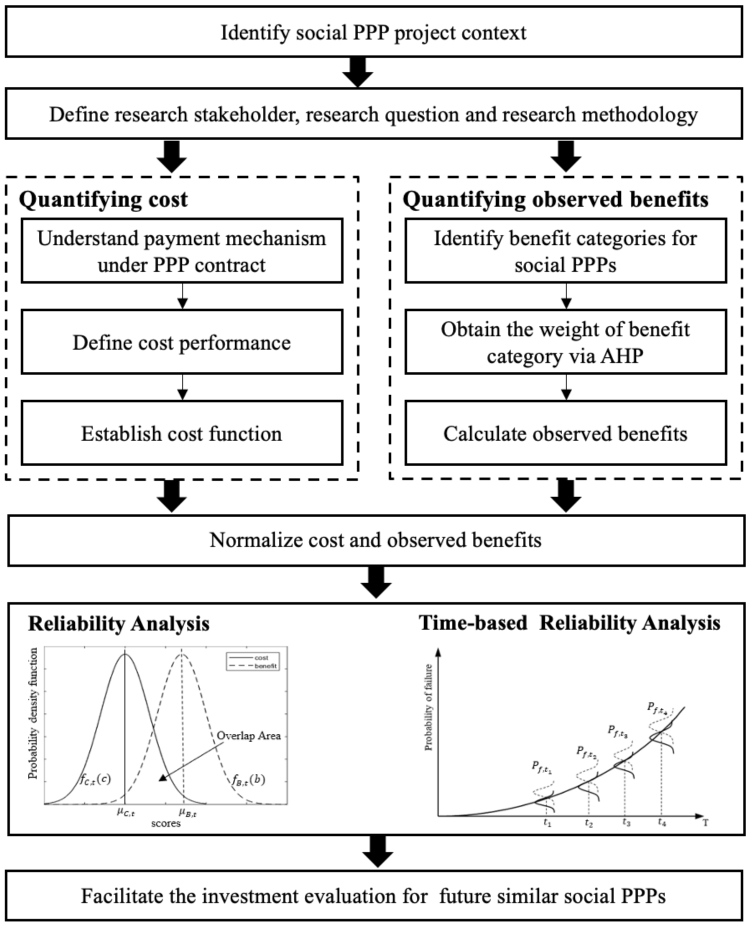

Fig 4. Reliability-based Evaluation Approach for Social PFI Investment

Discussion and Conclusions

Social PPPs has been playing an important role in society development but also exposed to more uncertainty. Government's investment evaluations of social PPPs are dominated using the public sector comparator (PSC) approach. This approach compares the risk adjusted, whole of life estimate of 'normal' government delivery with that offered by the private sector, which provides a best estimate of the project at pretender, but the approach lacks a mechanism to consider changes over time and non-monetary benefit in social PPPs. This is particularly highlighted when considering the reality of service outcomes obtained via PPP procurement. This paper seeks to improve current social PPPs infrastructure decision-making approach by incorporating time-based scenarios and tests of the reliability of costs and non-benefit benefits into the investment decision process.

The proposed approach is mainly contributed to two parts, one of which is to consider non-monetary benefit of social PPPs into investment decisions and the other is to assess investment uncertainty using engineering reliability analysis to better measure the value for money of social PPPs. Admittedly, some drawbacks inevitably exist. Firstly, this approach considers only non-monetary benefit of social PPPs in terms of delivery of service (DoS) and attracting and retaining the Public ($ARtP$) into investment evaluation, while a broad picture needed to be painted for all-sided benefit profile and sub-items, such as environmental, social, innovation, etc. in the future research. Secondly, due to the unavaliability of data in current stage, testing of this improved investment approach has to be conducted in future studies once the intact and authentic data can be obtained. In addition, the indicators in this approach could be changed when analyzing other types of social PPP project, but the methodology is applicable. Consequently, for further studies, this reliability-based investment evaluation has potential to consider full-scale social-environmental cost and benefit of social PPPs into investment evaluation and conduct sensitivity analysis on investment uncertainty. Most importantly, this approach can be developed to evaluate social infrastructure sustainability, incorporating more refined wider economic or social impact analysis, which could encourage to achieve more VFM in social PPPs infrastructure projects.

Reference

[1] J. Tan and J. Z. Zhao, “The Rise of Public–Private Partnerships in China: An Effective Financing Approach for Infrastructure Investment?,” *Public Adm Rev*, vol. 79, no. 4, 2019, doi: 10.1111/puar.13046.

[2] M. N. Gebremeskel, S. Y. Kim, L. D. Thuc, and M. V. Nguyen, “Forming a driving index for implementing public-private partnership projects in emerging economy: Ethiopian perception,” *Engineering, Construction and Architectural Management*, vol. 28, no. 10, 2021, doi: 10.1108/ECAM-06-2020-0459.

[3] E. Cheung, A. P. C. Chan, and S. Kajewski, “Reasons for implementing public private partnership projects: Perspective from Hongkong, Australian and British practitioners,” *Journal of Property Investment and Finance*, vol. 27, no. 1, 2009, doi: 10.1108/14635780910926685.

[4] The World Bank, “Private Participation in Infrastructure (PPI) 2021 Annual Report,” 2021.

[5] E. Engel, R. Fischer, and A. Galetovic, “The basic public finance of public-private partnerships,” *J Eur Econ Assoc*, vol. 11, no. 1, 2013, doi: 10.1111/j.1542-4774.2012.01105.x.

[6] Y. Ke, W. Hao, H. Ding, and Y. Wang, “Factors influencing the private involvement in Urban rail public-private partnership projects in China,” *Construction Economics and Building*, vol. 17, no. 1, 2017, doi: 10.5130/AJCEB.v17i1.5105.

[7] F. Zhang and B. Yu, “Value-for-Money Drivers of PPP Projects in China,” *Journal of Management in Engineering*, 2017.

[8] P. Burger and I. Hawkesworth, “How to attain value for money: comparing PPP and traditional infrastructure public procurement. OECD Journal on Budgeting,” 2011.

[9] A. Boardman and M. Hellowell, “A comparative analysis and evaluation of specialist PPP units’ methodologies for conducting value for money appraisals,” *Journal of Comparative Policy Analysis: Research and Practice*, vol. 19, no. 3, pp. 191–206, 2017.

[10] The world of Bank, “Assessing Value for Money of the PPP,” *PPPLRC Public-Private Partnership Legal Resource Center*, Jun. 24, 2022.

[11] J. Liu, P. E. D. Love, J. Smith, M. Regan, and M. Sutrisna, “Public-private partnerships: a review of theory and practice of performance measurement,” *International Journal of Productivity and Performance Management*, 2014.

[12] J. Song, Y. Hu, and Z. Feng, “Factors Influencing Early Termination of PPP Projects in China,” *Journal of Management in Engineering*, vol. 34, no. 1, 2018, doi: 10.1061/(asce)me.1943-5479.0000572.

[13] G. Atmo and C. Duffield, “Improving investment sustainability for PPP power projects in emerging economies: Value for money framework,” *Built Environment Project and Asset Management*, vol. 4, no. 4, 2014, doi: 10.1108/BEPAM-10-2013-0051.

[14] P. E. D. Love, J. Liu, J. Matthews, C.-P. Sing, and J. Smith, “Future proofing PPPs: Life-cycle performance measurement and building information modelling,” *Autom Constr*, vol. 56, pp. 26–35, 2015.

[15] P. Harris, W. Mundy, and P. Lindwall, “Public infrastructure,” *Productivity Commission Inquiry Report*, vol. 1, no. 71, pp. 1–138, 2014.

[16] Infrastructure Partnerships Australia, “Performance of PPPs and Traditional Procurement in Australia,” 2010.

[17] Y. Ke, X. Liu, and S. Wang, "Equitable financial evaluation method for public-private partnership projects," *Tsinghua Sci Technol*, vol. 13, no. 5, pp. 702–707, 2008.

[18] C. Cui, Y. Liu, A. Hope, and J. Wang, "Review of studies on the public–private partnerships (PPP) for infrastructure projects," *International Journal of Project Management*, vol. 36, no. 5, pp. 773–794, 2018.

[19] L. Geng, N. Herath, L. Zhang, F. K. P. Hui, and C. Duffield, "Reliability-based decision support framework for major changes to social infrastructure ppp contracts," *Applied Sciences (Switzerland)*, vol. 10, no. 21, pp. 1–18, Nov. 2020, doi: 10.3390/app10217659.

[20] S. Sarkar, "On the investment–uncertainty relationship in a real options model," *J Econ Dyn Control*, vol. 24, no. 2, pp. 219–225, 2000.

[21] J. Liu, X. Yu, and C. Y. J. Cheah, "Evaluation of restrictive competition in PPP projects using real option approach," *International journal of project management*, vol. 32, no. 3, pp. 473–481, 2014.

[22] B. Li, A. Akintoye, P. J. Edwards, and C. Hardcastle, "Critical success factors for PPP/PFI projects in the UK construction industry," *Construction Management and Economics*, vol. 23, no. 5, 2005, doi: 10.1080/01446190500041537.

[23] G. A. Hodge and C. Greve, "On public–private partnership performance: A contemporary review," *Public Works Management & Policy*, vol. 22, no. 1, pp. 55–78, 2017.

[24] J. K. Roehrich, M. A. Lewis, and G. George, "Are public-private partnerships a healthy option? A systematic literature review," *Soc Sci Med*, vol. 113, 2014, doi: 10.1016/j.socscimed.2014.03.037.

[25] M. N. Haque, M. Saroar, M. A. Fattah, and S. R. Morshed, "Public-Private Partnership for achieving sustainable development goals: a case study of Khulna, Bangladesh," *Public Administration and Policy*, vol. 23, no. 3, 2020, doi: 10.1108/PAP-04-2020-0023.

[26] Norton Rose Fulbright, "Public-Private Partnership and the Private Finance Initiative," *LEXOLOGY*, Apr. 24, 2020.

[27] S. Lima, A. Brochado, and R. C. Marques, "Public-private partnerships in the water sector: A review," *Util Policy*, vol. 69, 2021, doi: 10.1016/j.jup.2021.101182.

[28] L. M. English, "Using public-private partnerships to achieve value for money in the delivery of healthcare in Australia," *Int J Public Pol*, vol. 1, no. 1–2, 2005, doi: 10.1504/ijpp.2005.007795.

[29] L. Bing, A. Akintoye, P. J. Edwards, and C. Hardcastle, "The allocation of risk in PPP/PFI construction projects in the UK," *International Journal of Project Management*, vol. 23, no. 1, 2005, doi: 10.1016/j.ijproman.2004.04.006.

[30] PPPLRC, "PPP Reference Guide-PPP Basics," Apr. 2017.

[31] D. de Castro e Silva Neto, C. O. Cruz, F. Rodrigues, and P. Silva, "Bibliometric analysis of PPP and PFI literature: Overview of 25 years of research," *J Constr Eng Manag*, vol. 142, no. 10, p. 6016002, 2016.

[32] M. Davern *et al.*, "Using spatial measures to test a conceptual model of social infrastructure that supports health and wellbeing," *Cities Health*, vol. 1, no. 2, 2017, doi: 10.1080/23748834.2018.1443620.

[33] M. M. Marzouk and M. O. Elhesnawi, "Developing an integrated risk management system for evaluating ppp projects in Libya," *Journal of Engineering and Applied Science*, vol. 66, no. 5, 2019.

[34] S. Mishra, S. Khasnabis, and S. L. Dhingra, "A simulation approach for estimating value at risk in transportation infrastructure investment decisions," *Research in Transportation Economics*, vol. 38, no. 1, 2013, doi: 10.1016/j.retrec.2012.05.009.

[35] T. S. Ong and C. H. Thum, "Net Present Value and Payback Period for Building Integrated Photovoltaic Projects in Malaysia," *International Journal of Academic Research in Business and Social Sciences*, vol. 3, no. 2, 2013.

[36] B. C. Kim, E. Shim, and K. F. Reinschmidt, "Probability distribution of the project payback period using the equivalent cash flow decomposition," *Engineering Economist*, vol. 58, no. 2, 2013, doi: 10.1080/0013791X.2012.760696.

[37] D. C. Major, "Benefit-Cost Ratios for Projects in Multiple Objective Investment Programs," *Water Resour Res*, vol. 5, no. 6, 1969, doi: 10.1029/WR005i006p01174.

[38] S. H. Rukmana and M. A. Muslim, "Decision Support System Based on Benefit Cost Ratio Method for Project Tender," *APTIKOM Journal on Computer Science and Information Technologies*, vol. 2, no. 1, 2020, doi: 10.34306/csit.v2i1.66.

[39] S. Chaudhuri and R. Chaudhuri, "A COST BENEFIT ANALYSIS OF DELHI AIRPORT PPP PROJECT," *Journal of Air Transport Studies*, vol. 8, no. 1, 2017, doi: 10.38008/jats.v8i1.38.

[40] H. Gaspars-Wieloch, "Project Net Present Value estimation under uncertainty," *Cent Eur J Oper Res*, vol. 27, no. 1, 2019, doi: 10.1007/s10100-017-0500-0.

[41] V. A. C. De Albornoz, A. L. Galera, and J. M. Millán, "Is it correct to use the internal rate of return to evaluate the sustainability of investment decisions in Public private partnership projects?," *Sustainability (Switzerland)*, vol. 10, no. 12, 2018, doi: 10.3390/su10124371.

[42] M. Kamel, R. Khallaf, and I. Nosaier, "Net present value-time curve behaviour of public private partnership projects," *International Journal of Construction Management*, 2022, doi: 10.1080/15623599.2022.2025742.

[43] N. Nguyen, K. Almarri, and H. Boussabaine, "A risk-adjusted decoupled-net-present-value model to determine the optimal concession period of BOT projects," *Built Environment Project and Asset Management*, vol. 11, no. 1, 2021, doi: 10.1108/BEPAM-12-2019-0134.

[44] M. Siemiatycki and N. Farooqi, "Value for money and risk in public–private partnerships: Evaluating the evidence," *Journal of the American Planning Association*, vol. 78, no. 3, pp. 286–299, 2012.

[45] J. Y. Kweun, P. K. Wheeler, and J. L. Gifford, "Evaluating highway public-private partnerships: Evidence from US value for money studies," *Transp Policy (Oxf)*, vol. 62, pp. 12–20, 2018.

[46] R. Akbiyikli, "Value for money (VFM) evaluation in PPP projects: An overview," 2017.

[47] D. Grimsey and M. K. Lewis, *Global developments in public infrastructure procurement: Evaluating public-private partnerships and other procurement options*. 2017. doi: 10.4337/9781785366192.

[48] O. HELBY PETERSEN, "Evaluating the costs, quality, and value for money of infrastructure public-private partnerships: a systematic literature review," *Annals of public and cooperative economics*, vol. 90, no. 2, pp. 227–244, 2019.

[49] M. Siemiatycki and N. Farooqi, "Value for money and risk in public–private partnerships: Evaluating the evidence," *Journal of the American Planning Association*, vol. 78, no. 3, pp. 286–299, 2012.

[50] C. Ameyaw, T. Adjei-Kumi, and D.-G. Owusu-Manu, "Exploring value for money (VfM) assessment methods of public-private partnership projects in Ghana: a theoretical framework," *Journal of Financial Management of Property and Construction*, 2015.

[51] K. Ismail, R. Takim, and A. H. Nawawi, "A public sector comparator (PSC) for value for money (VFM) assessment tools," *Asian Soc Sci*, vol. 8, no. 7, p. 192, 2012.

[52] K. Ismail, R. Takim, and A. H. Nawawi, "The evaluation criteria of Value for Money (VFM) of Public Private Partnership (PPP) bids," in *International Conference on Intelligent Building and Management*, 2011, vol. 5, pp. 349–355.

[53] D. Morallos and A. Amekudzi, "The state of the practice of value for money analysis in comparing public private partnerships to traditional procurements," *Public Works Management & Policy*, vol. 13, no. 2, pp. 114–125, 2008.

[54] The Organisation for Economic Co-operation and Development, *Value for Money in Government*. 2015.

[55] The Organisation for Economic Co-operation and Development, *Value for Money in Government* . 2013.

[56] A. S. Gorshkov, P. P. Rymkevich, D. V Nemova, and N. I. Vatin, "Method of calculating the payback period of investment for renovation of building facades," *Stroitel'stvo Unikal'nyh Zdanij i Sooruzenij*, no. 2, p. 82, 2014.

[57] K. Brzozowska, "Cost-Benefit Analysis in Public Project Appraisal," *Engineering Economics*, vol. 53, no. 3, 2007.

[58] T. Söderqvist, P. Brinkhoff, T. Norberg, L. Rosén, P. E. Back, and J. Norrman, "Cost-benefit analysis as a part of sustainability assessment ofremediation alternatives for contaminated land," *J Environ Manage*, vol. 157, 2015, doi: 10.1016/j.jenvman.2015.04.024.

[59] P. Brinkhoff, T. Norberg, L. Ros, and J. Norrman, "Cost-benefit analysis as a part of sustainability assessment of remediation alternatives for contaminated land," *J Environ Manage*, vol. 157, pp. 267–278, 2015, doi: 10.1016/j.jenvman.2015.04.024.

[60] Z. Ding, X. Cao, Y. Wang, H. Wu, J. Zuo, and G. Zillante, "Cost-benefit analysis of demolition waste management via agent-based modelling: A case study in Shenzhen," *Waste Management*, vol. 137, pp. 169–178, 2022, doi: https://doi.org/10.1016/j.wasman.2021.10.036.

[61] K. Kim, J. Kim, and D. Yook, "Analysis of features affecting contracted rate of return of Korean ppp projects," *Sustainability (Switzerland)*, vol. 13, no. 6, 2021, doi: 10.3390/su13063311.

[62] S. Verweij, "Once The Shovel Hits the Ground: Evaluating the Management of Complex Implementation Processes of Public-Private Partnership Infrastructure Projects with Qualitative Comparative Analysis," *SSRN Electronic Journal*, 2015, doi: 10.2139/ssrn.2646785.

[63] S. A. Mohammed, D. Colin, and H. F. K. Peng, "An enhanced framework for assessing the operational performance of public-private partnership school projects," *Built Environment Project and Asset Management*, vol. 8, no. 2, pp. 194–214, Jan. 2018, doi: 10.1108/BEPAM-07-2017-0041.

[64] J. Liu, P. E. D. Love, P. R. Davis, J. Smith, and M. Regan, "Performance measurement framework in PPP projects," in *P3BooK Proceedings of International Conference on PPP Body of Knowledge in Preston, UK, University of Central Lancashire, Lancashire*, 2013, pp. 55–64.

[65] S. Xu, S. Liu, L. Cheng, J. Gao, and P. Chen, "Comparative Study on Financial Calculation Indicators of PPP Project," in *IOP Conference Series: Materials Science and Engineering*, 2019, vol. 688, no. 5, p. 55032.

[66] J. Liu, P. E. D. Love, M. C. P. Sing, J. Smith, and J. Matthews, "PPP social infrastructure procurement: Examining the feasibility of a lifecycle performance measurement framework," *Journal of infrastructure systems*, vol. 23, no. 3, p. 4016041, 2017.

[67] US Department of Transportation, "Value for money assessment for Public-Private Partnerships: A primer.," Washington, 2012.

[68] K. S. Pribadi, P. Soekirno, and M. Husnullah Pangeran, "Integrating qualitative and quantitative risk analysis for investment in public-private partnership scheme for water supply in Indonesia," in *Construction and Professional Practices - Proceedings of the 10th East Asia-Pacific Conference on Structural Engineering and Construction, EASEC 2010*, 2006, vol. 5.

[69] C. Sun, N. Li, and Y. Zhang, "Study on Qualitative Evaluation Index System of VFM in PPP Project," in *IOP Conference Series: Earth and Environmental Science*, 2019, vol. 267, no. 3. doi: 10.1088/1755-1315/267/3/032041.

[70] J. Martins, R. C. Marques, and C. O. Cruz, "Maximizing the value for money of PPP arrangements through flexibility: An application to airports," *J Air Transp Manag*, vol. 39, 2014, doi: 10.1016/j.jairtraman.2014.04.003.

[71] R. Pellegrino, N. Vajdic, and N. Carbonara, "Real option theory for risk mitigation in transport PPPs," *Built Environment Project and Asset Management*, vol. 3, no. 2, 2013, doi: 10.1108/BEPAM-05-2012-0027.

[72] Department of Infrastructure and Regional Development, "National Public Private Partnership Guideline Volume 5: Discount Rate Methodology Guidance," Canberra, 2013.

[73] J. Lai, L. Zhang, C. Duffield, and L. Aye, "Economic risk analysis for sustainable urban development: Validation of framework and decision support technique," *Desalination Water Treat*, vol. 52, no. 4–6, pp. 1109–1121, 2014.

[74] United Nations, "Transforming our World: The 2030 Agenda for Sustainable Development," 2015.

[75] B. Y. P. Leung and E. C. M. Hui, "Evaluation approach on public-private partnership (PPP) urban redevelopments," *International Journal of Strategic Property Management*, vol. 9, no. 1, 2005, doi: 10.1080/1648715X.2005.9637522.

[76] D. Baloi and A. D. F. Price, "Modelling global risk factors affecting construction cost performance," vol. 21, pp. 261–269, 2003, doi: 10.1016/S0263-7863(02)00017-0.

[77] B. R. Mckim, T. Hegazy, and M. Attalla, "Project Performance Control in Reconstruction Projects," *J Constr Eng Manag*, vol. 126, no. April, pp. 137–141, 2000.

[78] H. J. Liu, P. E. D. Love, J. Smith, Z. Irani, N. Hajli, and M. C. P. Sing, “From design to operations: a process management life-cycle performance measurement system for Public-Private Partnerships,” *Production Planning & Control*, vol. 29, no. 1, pp. 68–83, 2018.

[79] M. I. Praveen Thokala, Nancy Devlin, Kevin Marsh, Rob Baltussen, Meindert Boysen, Zoltan Kalo, Thomas Longrenn, Filip Mussen, Stuart Peacock, John Watkins, “Multiple Criteria Decision Analysis for Health Care Decision Making—An Introduction: Report 1 of the ISPOR MCDA Emerging Good Practices Task Force,” *Eur J Oper Res*, 2018.

[80] C. Macharis and A. Bernardini, “Reviewing the use of Multi-Criteria Decision Analysis for the evaluation of transport projects : Time for a multi-actor approach,” *Transp Policy (Oxf)*, vol. 37, pp. 177–186, 2015, doi: 10.1016/j.tranpol.2014.11.002.

[81] L. K. Singh, M. K. Jha, and V. M. Chowdary, “Multi-criteria analysis and GIS modeling for identifying prospective water harvesting and artificial recharge sites for sustainable water supply,” *J Clean Prod*, vol. 142, 2017, doi: 10.1016/j.jclepro.2016.11.163.

[82] G. Baudry, C. Macharis, and T. Vallée, “Range-based Multi-Actor Multi-Criteria Analysis : A combined method of Multi-Actor Multi-Criteria Analysis and Monte Carlo simulation to support participatory decision making under uncertainty,” *Eur J Oper Res*, vol. 264, pp. 257–269, 2018, doi: 10.1016/j.ejor.2017.06.036.

[83] P. Raisbeck, C. Duffield, and M. Xu, “Comparative performance of PPPs and traditional procurement in Australia,” *Construction management and economics*, vol. 28, no. 4, pp. 345–359, 2010.

[84] M. Hueskes, K. Verhoest, and T. Block, “Governing public–private partnerships for sustainability: An analysis of procurement and governance practices of PPP infrastructure projects,” *International journal of project management*, vol. 35, no. 6, pp. 1184–1195, 2017.

[85] N. Subramanian and R. Ramanathan, “A review of applications of Analytic Hierarchy Process in operations management,” *Intern. Journal of Production Economics*, vol. 138, no. 2, pp. 215–241, 2012, doi: 10.1016/j.ijpe.2012.03.036.

CENTRALISED OPERATION OF RESIDENTIAL BUILDINGS: A CASE STUDY OF THE OLD BUDAPEST

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Abstract
With the age of Big Data in Facility Management, new systems of centralised operation are now available. How do those systems meet inhabitants' requirements? As a case study from the past, socialist Budapest provides 40 years of experience for developers of new building operation systems.
Budapest's residential housing stock was operated by a single mega organisation, one centralised, state-owned company. The author has researched historical Budapest records of building operation from 1950 to 1985, gathering data on the resources used for maintenance and renovation. In parallel, data were gathered on customer satisfaction based on selected local daily publications. Under Hungarian Socialism, the residential segment and housing was a topic about which the public had limited opportunities to voice their criticism. This criticism appeared in various forms: letters to the editor, jokes and journalist reports. The housing stock, the applied resources and inhabitants' opinions were analysed together in order to identify trends in the period of centralised operation.
The study may be used as a significant input for new, intelligent systems of centralised Facility Management; however, the study's applicability may be limited as the political context changes.

Peer-review under responsibility of the scientific committee of the Creative Construction Conference 2023.

Keywords: Centralisation, Facility Management, Property Management, Socialism.

1. Introduction, relevance of the subject, hypothesis

Now considered common knowledge, the real estate sector, and more specifically real estate operation, is entering a revolutionary new era. With Big Data, Artificial Intelligence (AI) and the Internet of Things (IoT), new, larger than ever, centralised operation systems can be created. The expected benefits of this new era are well known; however, many years of experience are still needed to be able to obtain and evaluate practical results and consequently fine-tune those systems. The research presented here aims to build on the knowledge of the past to inform the future design and deployment of large real estate operation systems.

The period of socialism in Hungary (1946-1990) can be considered as a kind of great experimental laboratory. As such, the period has been interpreted as a societal "Petri dish" by scholars who wrote critical analyses of socialism as a social order (see [1], [2] and [3]). We believe that this period and its social phenomena can also provide useful lessons for the new era of the real estate sector (see our previous study on the SMART initiative's forerunner [4]). During the various periods of socialist central control in Hungary, increasing resources were allocated to the maintenance and repair of housing units. In Budapest, building operation was centralised to a significant extent during this period. In this study, we wish to examine how end-users, i.e. residential perceptions, reflected the increase in resources; simply put, whether the additional expenditure incurred by centralisation paid off.

Our analysis here is not based on using Market Value, as defined by the RICS [5], but the "community value", or "public good", which is becoming increasingly common in housing market analysis [6]. This approach is independent of the prevailing market and price level, so the results obtained in this way can be independent of the economic factors at the time and their changes over time. Under socialism, the community's opinion, the "voice" (see Kornai for details, [3]) was mainly expressed through the various press products, and the press amplified that voice towards decision-makers and bureaucrats.

Accordingly, the research uses a statistical approach to the contemporary press thereby mapping the methodology of Stated Preference of community evaluation [7].

The hypothesis of the research is that the increase in resources allocated to centralised operation in socialist Budapest increased inhabitants' satisfaction.

The research period starts in 1960, following the post-World War II reconstruction cycle and the consolidation period after the Hungarian Revolution of 1956. The period ends in 1985 with the beginning of the mass privatisation of public housing, making the overall study period 25 years.

After the introduction above, the study follows the following structure: the first section presents the relevant literature, first the history of socialist housing operation, and then the literature on modern, centralised real estate operation. The second section describes the research methodology and the data sources used. The third section presents the research findings, and, in the final section, the lessons promised in the introductory part are drawn, the hypothesis is evaluated, the limitations of the research are described and the future research programme is presented.

2. Literature research

Socialism in Hungary lasted from 1948, "the year of the turning point", until the change of regime in 1989, and this period can be divided into four phases [8]. The first phase between 1948 and 1953 was the period of post-war reconstruction in terms of the housing market, and the institutional system of forced centralisation was also established then. The defining event of the second phase is the 1956 Revolution and the slow consolidation that followed, a period of turbulence that is also not suitable for our analysis. The third period, from 1960 onwards, is called the early Kádár era, while the later years of Kádárism, known as Goulash Communism, lasted until the regime change in 1989. During this period, from 1985 onwards, mass privatisation of housing began [9], and with that the erosion of the previously established centralised system [10]. As such, the period chosen for the present study stretches from 1960 to 1985, which can be considered as a roughly homogeneous period from the aspect of the real estate market.

Hungarian housing statistics have a long tradition, with very long time series and comprehensive analyses available [11]. However, the detailed data of the period are only available in processed form, and there is no doubt that authors of the period interpreted such data according to the political needs of the moment. It is against this background that we need to assess the available data publications and statements.

The housing stock of Budapest changed significantly over the period. The Second World War caused enormous damage to Budapest's housing stock. According to the data of the census of March 1945, more than 70 percent of all residential buildings in Budapest, i.e. over 66,000 housing units, were damaged, of which 23.1 percent were severely damaged and 3.8 percent (13,588 residential units) were completely destroyed [12]. Data on housing construction in Budapest during the period under review is shown in Figure 1. The total number of housing units built exceeded 300,000, resulting in an increase of nearly seventy percent on the previous housing stock. At the same time, overcrowding did not decrease and housing shortages persisted [13].

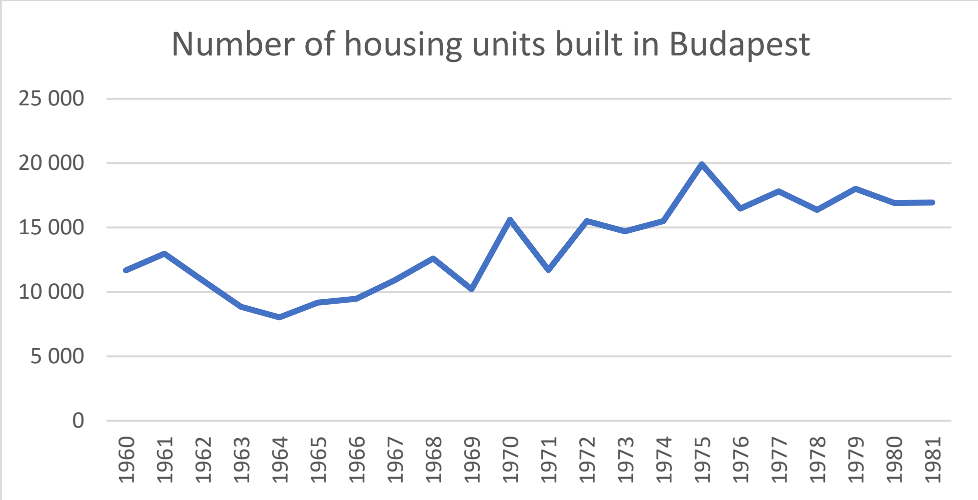

Fig. 1. Number of newly built housing units in Budapest. Source: [14]

In the period under review, i.e. from 1960 to 1985, the central body of state construction management was the Ministry of Construction and Urban Development [15]. The first department of the Ministry was responsible for housing management, while the sixth department was responsible for real estate operation [15]. The actual functions of housing operation were transferred to state or local council-owned companies [16]. In Budapest, the Budapest Property Management Company (Fővárosi Ingatlankezelő Vállalat, FIK) and its directorates coordinated the tasks related to the operation and maintenance of state-owned real estate [17], so, in today's real estate terminology, FIK performed property management tasks.

Nationalisation was a key step in the centralisation of housing management. In 1952, all properties with more than six rooms and all state-owned corporate properties with more than 50% state ownership were transferred to the ownership of and managed by the Hungarian State [18]. The institutionalisation of property management continued until 1960. Direct supervision was transferred from the state to the city councils, which set up property management companies for implementation purposes. From 1960, records were added to a unified technical register, and this date marks the beginning of an institutionalised and permanent centralised operation [15]. In 1971, a so-called housing reform was introduced, which regulated and partially opened up the housing market [19]. A change of approach occurred in 1981, when the government made housing modernisation and maintenance a priority, recognising that mass construction could not address a significant part of society's housing problem [17].

Housing management served as a channel for defusing social tensions, and was one of the few topics on which the population could express their opinions and criticisms [1]. This opinion was the social "voice" that appeared in public discourse, in the daily and weekly press, in literary works and in films [3]. There are countless examples of this, but, in Hungarian film art, films parodying the housing situation were released almost every year. Undoubtedly, the publications of the period do not represent a complete record of public discourse, but their intensity, or changes in intensity, became significant pieces of information.

Real estate operation, or Facility Management (FM) in broader terms, is increasingly characterised by centralisation [20]. Integration is possible through the combined deployment of Building Information Modelling (BIM), and the Internet-based sensors and actuators (commonly called IoT) developed in conjunction with it [21]. The solution is a combination of decentralised control tools and centralised management. This minimises the use of human resources while keeping energy costs at an optimal level. Such an automated system is easily adaptable and meets flexibility requirements [22].

Various communities, large companies and municipalities have chosen and are choosing to centralise FM activities. In Sri Lanka, the FM integration of similar companies has been proposed by Weerasinghe and Sandanayake [23]. In Denmark, 96 municipal FM organisations have been merged into a central system [24]. Goulden and Spence [25] argue that, in energy procurement practice, centralised FM service providers have greater business opportunities. According to Per Anker, the centralisation of FM is an advantage for international firms, as it simplifies the management of their business partners [26]. Overall, the relevant literature cited here as an example clearly favours the centralisation of FM systems, in other words real estate operation.

3. Research methodology

The literature of the period, which is still available today, is of course rather limited, but there is a summary publication that provides a comprehensive, chronological picture of the real estate operation of Budapest [16]. The data presented in this publication were compared with other available sources and, as they were found to be of a reasonable order of magnitude, this data set was used for the maintenance and renovation section. The national data for centralised real estate operation are not known in aggregate, as they were allocated to separate regional companies and their reports were not made public. Therefore, in this research we assumed that the change in volumes in the capital and the change in national volumes (over the period under study) occurred proportionately. Data on the expenditure in Budapest are shown in Table 1 below. Please note that there were no significant price increases in the period under review, so any inflationary effect can be discounted in the following analyses.

Table 1. Housing operation expenditures of the municipality of Budapest. Source: own editing

	1951	1952	1962	1970	1972	1975	1980	1981	1982
Number of buildings managed by the capital	14,848	34,326	35,573		35,264				
Number of flats managed by the capital	176,250	358,504	388,289		400,776				
Proportion of flats to the total of housing units in Budapest	37.90%				60.50%				
Amount spent on housing renovation (million HUF)	0	0	620	518	1,027	702	1,056	1,255	1,483
Amount spent on housing maintenance (million HUF)	29	148	380	336	513	558	1,072	1,248	1,341
Housing maintenance cases (units)	33,773	197,036	656,196		441,299				
Total number of blue-collar employees of Budapest's property management companies				5,360		5,845	6,043	6,077	6,083

The Arcanum Digital Repository (www.arcanum.hu) and its built-in search engine were used for the social "voice",. This data repository contains the Hungarian press products, including national and county newspapers and weekly publications, in a digital and searchable form. Some specific journals have not yet been digitised in the repository, but those presumably also provided less space for the community "voice" to be heard. The database provides a unique opportunity to study the contemporary press, and is used by researchers from a wide range of disciplines.

The 1949 Constitution declared freedom of the press to be implemented "in the interests of the workers". In the socialist period, the press was neither free nor independent, but people of the time could read "between the lines" and editors, depending on their individual preferences, did send such messages to the public [27].

In the Arcanum Digital Repository, we conducted a systematic search for word combinations that deal with the quality and maintenance of housing and its shortcomings and that may have appeared in nationally distributed newspapers. The search terms given in various combinations were: Property Manager, IKV1, Housing Unit, Complaint, Fault. For the period between 1960 and 1985, these complex searches returned results in about 300 publications. After reviewing each of those results, 216 different

[1] Common Hungarian abbreviation for Property Management Company

and relevant publications were found. Since the location concerned could not always be identified, it was assumed that the intensity of the national records was the same as that of Budapest.

The 216 “voices of complaint” were processed as a time series and the results are shown in Figure 2 below. The number of records increases over time, with a clear surge in the late sixties, but the trend seems to have stabilised from 1971 onwards. Without doubt, these publications could have been influenced by several factors: on the one hand, newspaper editors select the topics, and, due to external or internal editorial principles (censorship) they cannot publish the same topic several times. On the other hand, the loosening up of the socialist system provided steadily increasing (of course still limited) freedom of speech, and negative opinions could become more easily heard. Given the very large number of press products included in the survey (4383 titles at the time of the query), we believe that these two aspects result in minimal bias.

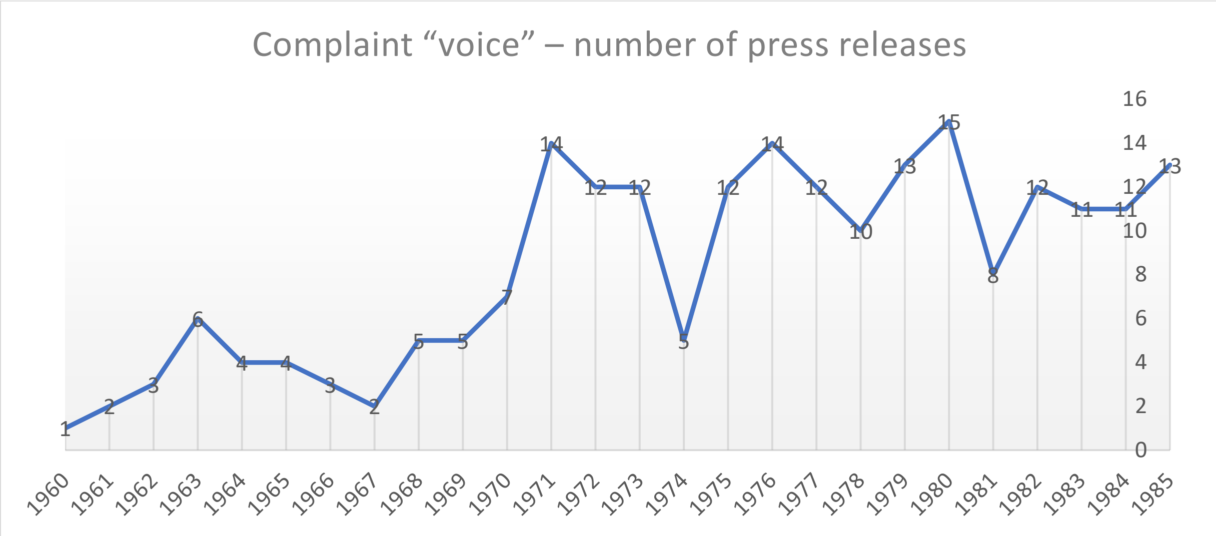

Fig. 2. Complaint "voice" - number of press releases. Source: own research

4. Research findings and their interpretation

The previous chapter presented the basic data for the research. To test the hypothesis, we produced a time series of changes in the managed housing stock, using the number of housing units built and the known variables from previous years. This time series for the number of housing units was then compared with the time series for operation and maintenance extrapolated from existing data. A resource index per housing unit was generated from the known maintenance data (total annual expenditure, headcount of maintenance staff, number of cases). The index was constructed from the available variables using the following formula while taking into account the relative weight of each item:

Annual expenditure index = Maintenance amount per housing unit (HUF) + Maintenance cases per housing unit (number) + Physical maintenance staff per 100 housing units (staff headcount)

The annual breakdown of the expenditure index thus produced is shown in Figure 3.

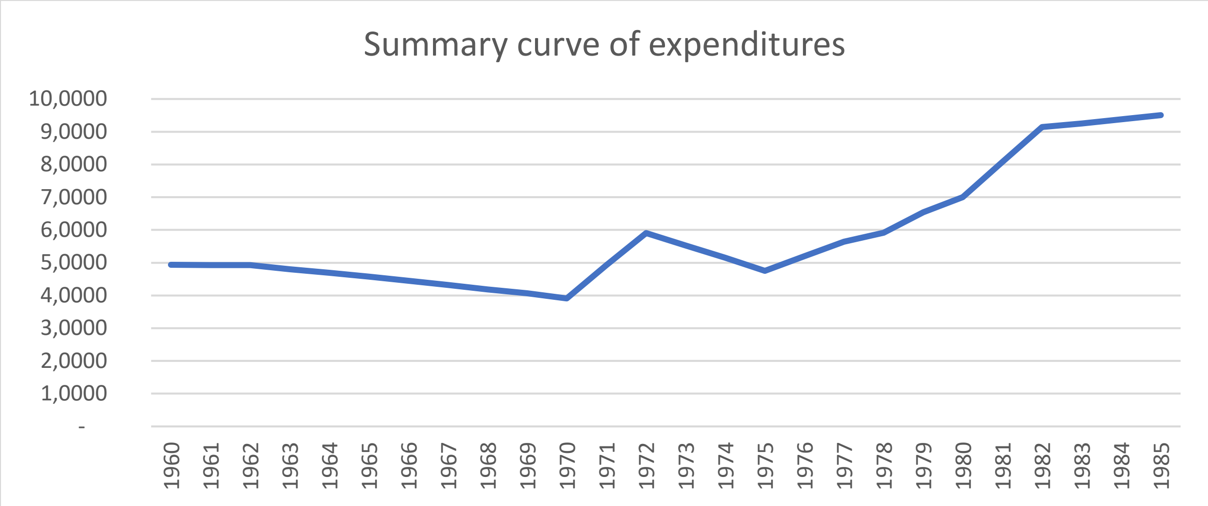

Fig. 3. Annual expenditure index Source: own editing

Comparing the second and third figures, it can be seen that the expenditure index is on an upward trend, while the number of complaints, i.e. the "voice", is static. The period 1971-1974, when expenditure increased significantly is interesting; in 1974, the number of complaints fell significantly, presumably (although it cannot be verified statistically) due to the allocation of additional resources. This is the period of housing reform referred to in the literature review. The community was generally positive about the changes, so this may have been one reason for the "voice" being silent for a while.

However, in later years, the expenditure index doubled, clearly indicating central efforts for the maintenance of the housing sector as dictated by politics. The public voice, however, remained the same in character as in previous years. Starting in 1980, the number of complaints fell by about a third and remained at this level. It can be seen that as the number of housing units increased, the "voice", i.e. the general dissatisfaction of society, did not become stronger, while the same "voice" did not react directly to the increase in expenditure, as the time series shows.

Our hypothesis that the increase in resources allocated to centralised operation increased the satisfaction of home-users is not supported by this research findings. At the same time, it can be concluded that, with the mobilisation of additional resources, the number of complaints in an increasingly liberated society stayed the same rather than increased.

5. Conclusion and further directions of research

Analysing the past can provide useful lessons for shaping our future. This universal truth is also applicable to the real estate sector. Another old saying is that social attitudes are deeply rooted and can only be shaped and reversed slowly. The findings of this research support this view: in the socialist Budapest of the past, society's "voice" did not become silent, even after centralisation and the doubling of expenditure, yet these expenditures and political efforts were sufficient to keep criticism at its usual level and not to increase it.

So what is the conclusion to be drawn from today's centralisation efforts? As the authors cited above argue, real estate operation and FM are moving towards centralisation. The trend cannot be stopped, but the creators of new systems must recognise that end-user attitudes are difficult to change. With proper communication and preparation, the intensity of complaints can be reduced, but it is expected that it will take a long time until the public do not criticise new initiatives but support them.

The present research is limited in that only partial expenditure data were available, and only the trend shown by them was used. If a complete time series can be found in archival data for an event in the period of socialism, the analysis will be richer and can be evaluated by statistical methods.

The socialist past in Hungary can serve as a good test case for analysing other recent changes in the real estate market. Such a test could be recommended on the efficiency of building management, the introduction of social housing units or the effectiveness of public regulation of real estate traffic.

References

[1] J. Kornai, A szocialista rendszer. Kritikai politikai gazdaságtan (The socialist system. Critical political economy). Budapest: Heti Világgazdaság Kiadói Rt, 1993.
[2] I. Szelényi, Társadalmi struktúra és lakásrendszer. Kandidátusi értekezés (Social structure and housing. Candidate thesis). 1972.
[3] J. Kornai, A hiány (The Shortage). Budapest: Közgazdasági és Jogi Könyvkiadó, 1982.
[4] I. Hajnal, Challenges in Operating SMART cities: lessons from the former socialist real estate sector of Hungary. 2022, o. 144. doi: 10.3311/CCC2022-017.
[5] International Valuation Standards Council, International Valuation Standards (IVS). 2022.
[6] P. Dolan és D. Fujiwara, “Happiness-Based Policy Analysis”, in The Oxford Handbook of Well-Being and Public Policy, M. D. Adler és M. Fleurbaey, Szerk., Oxford University Press, 2016, o. 0. doi: 10.1093/oxfordhb/9780199325818.013.9.
[7] I. Hajnal, “Stigmatizált ingatlanok értékcsökkenésének megállapítása” (Calculating the depreciation of stigmatised properties), 2020.
[8] Romsics I., Magyarország története a XX. században (History of Hungary in the 20th century). Osiris Kiadó, 2010.
[9] J. Balázs és I. Hajnal, Ingatlanvagyon, lakáspolitika és piacgazdaság Magyarországon és Svájcban (Real estate, housing policy and market economy in Hungary and Switzerland). Aula Könyvkiadó, 1994.
[10] K. Stanilov, The Post-Socialist City: Urban Form and Space Transformations in Central and Eastern Europe after Socialism. Springer Science & Business Media, 2007.
[11] G. Székely, „Száz év a magyarországi lakásstatisztikában” (One hundred years in Hungarian housing statistics), STATISZTIKAI Szle., köt. 98, sz. 6, o. 642–664, 2020, doi: 10.20311/stat2020.6.hu0642.
[12] J. Bertalan és B. Berti, „Lakásfejlesztési tevékenység Budapesten (1873-1973)” (Housing development in Budapest (1873-1973)), Budapest, köt. 12, 04 1974.
[13] P. Koncz, „Lakásállomány és lakásmobilizáció” (Housing stock and housing mobilisation), Városépítés, 1982.
[14] E. Nagy, „Budapesti lakásépítés múltja, örökségeink és adottságaink” (The past, heritage and potential of housing in Budapest), Városépítés, 1982.
[15] J. Kovács, Az építésügyi tárca szakirányításának története (History of the Department of Construction). Budapest: ÉTK, 2009.
[16] Á. Korda, „A fővárosi állami (IKV) kezelésű lakóházak fenntartási programjának végrehajtása, azzal kapcsolatos tapasztalatok” (The implementation of the maintenance programme of the state-managed (IKV) residential buildings of the capital city and related experiences), Magy. Épip., köt. 1983, sz. 9, 1983.
[17] A. Jantner, „A lakóházfenntartás helyzete, a megoldásra váró feladatok” (The situation of housing maintenance, the tasks to be solved), Magy. Épip., köt. XXXII, sz. 8, o. 449–455, 1983.
[18] G. Dános, Szerk., A fővárosi ingatlankezelő vállalatok 25 éve (25 years of the property management companies of Budapest). Budapest: Fővárosi Ingatlankezelő Vállalat, 1974.
[19] J. Hegedüs és I. Tosics, „Lakásosztályok és lakáspolitika; A budapesti lakáspiac irányításának változásai az elmúlt három évtizedben” (Housing classes and housing policy; changes in the management of the housing market in Budapest in the last three decades), Mozgó Világ, köt. 8, sz. 10, 1982.
[20] S. B. Nielsen, „Establishing of property centres”, in Facilities Management Models, Methods and Tools, Routledge, 2019.
[21] K. C. Dahanayake és N. Sumanarathna, “IoT-BIM-based digital transformation in facilities management: a conceptual model”, J. Facil. Manag., köt. 20, sz. 3, o. 437–451, jan. 2021, doi: 10.1108/JFM-10-2020-0076.
[22] D. Wei, B. Li, C. Wang, L. Wei, L. Zhang, és J. Yang, „IBMS + BIM + FM technology based intelligent building operation and maintenance management system design solution”, in 5th International Conference on Computer Information Science and Application Technology (CISAT 2022), SPIE, okt. 2022, o. 1195–1204. doi: 10.1117/12.2656285.
[23] R. Weerasinghe és Y. G. Sandanayake, „Integrated facilities management practices in Sri Lanka: a preliminary investigation”, 2013, Accessed on 13 April 2023. [Online]. Available: http://dl.lib.uom.lk/handle/123/17743
[24] S. Balslev Nielsen, „Centralizing Public FM organizations: Danish experiences with success criteria, results and realisation processes”, CFM Second Nord. Conf. 29-30 August 2016, 2016.
[25] M. Goulden és A. Spence, „Caught in the middle: The role of the Facilities Manager in organisational energy use”, Energy Policy, köt. 85, o. 280–287, okt. 2015, doi: 10.1016/j.enpol.2015.06.014.
[26] J. Per Anker, „International coordination of Facilities Management in multinational corporations.”, Jt. CIB Int. Symp. W055 W065 W089 W118 TG76 TG78 TG81 TG84, 2012.
[27] Attila H., A magyar sajtó története a szovjet típusú diktatúra idején (The history of the Hungarian press under the Soviet-style dictatorship). in Médiatudományi Könyvtár. Médiatudományi Intézet, 2013.

CHALLENGES IN ADOPTION OF PUBLIC PRIVATE PARTNERSHIPS FOR SOUTH AFRICAN INFRASTRUCTURE DEVELOPMENT

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Abstract

Public-private partnerships (PPPs) arrangements have proved to play a key role in the enhancement of the infrastructure development globally. South Africa’s adaptation of PPPs strategies in infrastructure development, allows the government and private sector to work together in the delivery of much-needed public infrastructure services. This paper aims to summarise the views of professionals in South Africa's public-private partnerships (PPPs) platform on significant challenges facing the market for PPPs or policy framework in South Africa, concerning the challenges and how can we approach them. To achieve the aim of this paper, both primary and secondary data was sourced. The secondary data was sourced through an in-depth review of the literature. Quantitative method was used to source secondary data; the data collected using a structured questionnaire. The sample of 50 respondents was approached to partake in a study, respondents included built-environment professionals from both the public and private sector who are knowledgeable about PPPs. 34 of the 50 completed and returned questionnaires (a response rate of 68%). Following analysing the data received, the findings revealed that PPPs is a feasible option to enhance the delivery of infrastructure in South Africa; however, the government is reluctant to partner with private sector. Findings further revealed that the main factors hindering the growth of PPPs utilisation in South Africa is lack of PPPs awareness and insufficient research on the PPPs model. Besides, skills shortage, policy bias toward traditional public procurement, tuning of municipal PPPs legislation besides capacity constraints were also found to be a problem. This research calls out to the infrastructure development entities to pay particular attention to skills development in both public and private sectors, in order to have capacity and ability to adopt PPPs model in infrastructure development and have equal responsibility in ensuring that PPPs are advanced accordingly. Moreover, expedite constructive discussions on the challenges addressed and jointly develop robust solutions.

Keywords: infrastructure development, public private partnerships, public private partnerships challenges.

1. Introduction

In the past 20 years, Public-Private Partnerships (PPPs) have been key item on the public agenda as a popular international strategy for enhancing infrastructure delivery. There has been much written on PPP over time, and a range of explanations have been canvassed. From the perspective of the OECD, PPPs are defined as “contractual agreements between the government and a private partner whereby the latter performs and funds public services using a capital asset while sharing the associated risk” [1]. PPPs in South Africa are essential models that can be utilised to enhance infrastructure delivery as envisioned on the Accelerated and Shared Growth Initiative for South Africa.

However, infrastructure development is the key element of the country’s development, economic growth, and social welfare. According to [2], infrastructure development is a catalyst that can be utilised to improve the economic growth and the social development of the country. Majority of developing nations are incapable of delivering sufficient critical infrastructure which results into the economy of the country collapsing due to the high deficit in a fiscal [3]. Therefore, the delivery of critical infrastructure through Public Private Partnerships (PPPs) could assist in narrowing the gap between the demand and the delivery of infrastructure that exists in developing countries. PPPs in South Africa are governed by the

Public Finance Management Act (PFMA), which ensures that the partnership that the public and private enter is beneficial to all the stakeholders.

In 2000, the South African National Treasury established the Public Private Partnerships (PPPs) Unit that will oversee the South African PPPs structure. The PPPs Unit plays a critical role in the establishment of PPPs as it has an authority to approve or disapprove proposed PPPs agreements [4]. According to [5], these partnerships are common and usual for all the stakeholders involved in the partnership to be critical of each party's approach and methodology concerning the partnership. According to [6], the dialogue of PPPs in South Africa has come to be characterised by scepticism and suspicion amongst the sectors in the PPP stage. This suspicion has limited productive discussions on how to adequately improve PPPs in the country. Furthermore, it is through the merger of the public and private sectors that we notice how impactful the unified partnership can be on service delivery. Despite this progress, there are different challenges that the PPP adaptation still faces, and this will be discussed in this research.

2. Literature Review

The public-private partnerships (PPPs) mean a commercial transaction between the government and the private organisation, and that organisation is handed over rights to deliver the service or asset on behalf of the government using their resources, expertise, and innovation; and utilise that service or asset for its commercial gain for an agreed period then hand it over to the government for free. [7] assumed that "PPPs are institutional and legal contractual partnership arrangements between the public and the private sector for the transfer of goods or services to the public." According to [8], PPPs arrangements are the long-term contract between the public and private sector whereby the private sector builds an infrastructure with their own money and resources, own and maintain it over the agreed period and all the risk lies with the private sector. In addition, public-private partnerships (PPPs) arrangement the private entity recoup the money they spent to develop an infrastructure by either charging the end user for the usage of the infrastructure are paid directly by the government over the agreed period [9]. [9] further stated that at the end of the contract the private sector hand over the infrastructure to the government at no cost, which is also viewed as an opportunity for the government to deliver infrastructure quicker without the associated ballooning of public debt.

According to [10], the public-private partnerships (PPPs) are becoming a more common method to deliver infrastructure assets around the world, which indicate that there is a fundamental shift in between the public and private sectors relationship. The common infrastructure projects that are delivered through PPPs are social and economic infrastructure projects i.e., hospitals, schools, prisons, transport infrastructure, water and sanitation plants and telecommunication [9]. Even though the PPPs are beneficial to both the government and the private sector entity; it is the government that is on the high gain side as the PPPs enables the government to deliver a much-needed public infrastructure at the shorten time with the use of private financing, and they get to deliver infrastructure to the public without bearing any risks, as the financial, construction, operations and maintenance risks are transferred to the private sector during the cession period.

2.1. Public-Private Partnerships Towards South African Infrastructure Development

The concept of the Public-private partnerships (PPPs) is a fairly new method of delivering infrastructure in South Africa, hence there are not many PPPs infrastructure assets that have been developed in the country thus far. Even though there have been efforts in the past two decades to improve the state of infrastructure in South Africa, however, the country is still struggling to find means to deal with political and institutional challenges that emerges during the implementation of PPPs arrangements. Delivering and managing services and public infrastructure through PPPs reflects as an excellent public management. [9], stated that benefits of utilising PPPs include the provision of finance by the private partner, substantial risk transfer away from the public sector and efficiency gains. [11] highlighted that even though PPPs arrangement are deemed to be fair and beneficial to all stakeholders, the private sector still needs to be monitored throughout the entire duration of the cession to ensure that quality is maintained.

2.2. Challenges Facing Public-Private Partnerships in South Africa

[12] alluded that Public-private partnerships (PPPs) projects normally take longer to implement than traditional procurement methods, and it is justifiable because it takes time and needs considerable attention to prepare for this kind of transactions. [13] further stated that leadership on PPPs at higher levels of government was lacking considerably, [9] supported this statement by stated that implementing agencies within government spheres were not aligned to acquire the set of skills that required to undertake the PPPs projects. Furthermore, there seems to be a lack of PPPs understanding from province to province, line department to line department and the PPPs knowledge is often not active at the highest political leadership level. Capacity and skills shortage was one of the critical challenges as enlisted by [9].

Sufficient time and resources are required for the country to have good Public-private partnerships (PPPs) agreements. Treasury looks at value for money, affordability and appropriate risk transfer, and it is important to note that meeting skill shortages should be a vital component of approval.

3. Research Methodology

The research methodology employed to collect, analyse and interpret data was thoroughly selected as the best method to achieve the aim of this study. Hence, a quantitative method was utilised to identify the challenges facing Public-private Partnerships (PPPs) for South African Infrastructure development. In addition, a quantitative method was used to collect, analyse and interpret data because it enables the researcher to easily describe the present status of what exists without manipulating any facts. The study was conducted in Republic South Africa, Gauteng province and the respondents for the study included built-environment professionals who are working for both the public and private sector and are knowledgeable about PPPs.

The sample for the study was selected using the purposive sampling, where 50 respondents were approached to partake in a study. Only 34 of the 50 completed and returned questionnaires (a response rate of 68%). Close-ended questionnaire was created using the literature reviewed and were distributed to the respondents in a link via email. The respondents chose their response using a five-point Likert scale, which was then converted into Mean Item Score (MIS) for each challenge. The content of the questionnaire for this study was structured in a manner that it strives to obtain as much accurate information as possible; to obtain the highest level of co-operation from the nominated respondents and that it is also easy to facilitate the collection and analysis of the data.

The data received was then analysed and interpreted using the IBM Statistical Package for Social Science (SPSS) to provide descriptive statistic results, i.e., mean item scores, frequency distributions and percentages

4. Findings and Discussion

4.1. Challenges in the adoption of Public-Private Partnerships (PPPs) in South Africa

Based on the ranking (R) of the relative importance indices for the listed factors (see Table 1.1). It is quite apparent through the median item score (MIS) that majority of the respondents indicated that there is insufficient capital to deploy successful PPP deals in South Africa for infrastructure development (R=1; MIS=4.07). Suspicion and mistrust amongst the sectors were ranked second (R=2; MIS=3.97), Government policies being biased towards traditional procurement was ranked third, and the lack of PPPs awareness was also ranked third with a score of 3.85 and followed by other challenges as shown in the table according to the MIS ranking.

Table 1: Challenges in the adoption of public private partnership in South Africa

CHALLENGES IN THE ADOPTION OF PUBLIC PRIVATE PARTNERSHIPS IN SOUTH AFRICA	MIS	R
Lack of capital	4.07	1
Suspicion and lack of trust between the public and private sectors	3.97	2
Policy Bias toward Traditional Procurement methods	3.85	3
Lack of PPPs awareness	3.85	3
The operational definition of PPPs remains unclear.	3.74	4
Insufficient research in PPPs	3.74	4
Public sector lacks understanding of PPPs	3.65	5
Skills shortages	3.47	6
External risks associated with PPPs	3.47	6
Inconsistent departmental priorities and commitment towards PPPs	3.47	6
Government structures are a problem in implementing PPPs Models.	3.44	7
Capacity constraints	3.44	7
Non-conducive environment for PPPs transactions	3.41	8
Lack of Resources dedicated towards PPPs implementation	3.38	9
PPPs are undesirable since they are costly to implement	3.15	10

Findings from the survey support that many challenges remain in Public-private Partnerships (PPPs) skills accumulation. [4], further states that disagreements between the two sectors is also a distinct challenge and this was clearly relayed in the findings. Insufficient funds for implementation of PPPs projects supports the work by [4]. One is persuaded to say that the capacity and the lack of skills is the influencing challenge towards the lack of implementing of PPPs project. In the absence of such capability, certain inherent inefficiencies associated with the public sector act as an inhibitor of the PPPs process.

5. CONCLUSION AND RECOMMENDATION

The success of Public-private Partnerships (PPPs) requires interaction and cooperation from different stakeholders, as well as the integration of different factors. The findings revealed that there is policy bias towards traditional procurement methods. Moreover, there is a lack of trust between the public and private sectors, and there are disagreements concerning risk transferring. Findings also reveal the lack of PPPs awareness and insufficient research on PPPs is a major challenge in adoption Public-private Partnerships (PPPs) in South Africa. The government still needs to pay particular attention to acquire PPPs related skills and use those skills find means to attract private sector to inject funds towards PPPs projects. The paper explored PPPs in South Africa and the challenges it currently faces. The results were verified against information obtained from a range of literature reviews on public-private partnerships. The study revealed that there are still essential challenges in fast-tracking infrastructure development and that the centre should be placed around Public-private Partnerships (PPPs) education.

References

[1] "A look at the challenges and governance of subnational public-private partnerships," Subnational Public-Private Partnerships, pp. 17–49, Nov. 2018, doi: 10.1787/9789264304864-3-en.

[2] C. Tengan, C. Aigbavboa, and W. Didibhuku Thwala, "Project management," Construction Project Monitoring and Evaluation, pp. 3–11, Apr. 2021, doi: 10.1201/9781003137979-1.

[3] K. Dithebe, C. O. Aigbavboa, W. D. Thwala, and A. E. Oke, "Analysis on the perceived occurrence of challenges delaying the delivery of water infrastructure assets in South Africa," Journal of Engineering, Design and Technology, vol. 17, no. 3, pp. 554–571, Mar. 2019, doi: 10.1108/jedt-10-2017-0101.

[4] Malao, M, Delivery of infrastructure development through public partnerships, Thesis, North West University, North West, 2011.

[5] M. Spackman, “Public–private partnerships: lessons from the British approach,” Economic Systems, vol. 26, no. 3, pp. 283–301, Sep. 2002, doi: 10.1016/s0939-3625(02)00048-1.

[6] T. Eloff, “Partnerships among Business, Government, and NGOs: Lessons from the South African National Business Initiative,” Evaluation & Development, pp. 213–220, Feb. 2018, doi: 10.4324/9781351323925-24.

[7] F. C. FOURIE and P. BURGER, “An Economic Analysis and Assessment of Public - Private Partnerships (PPPs),” The South African Journal of Economics, vol. 68, no. 4, pp. 305–316, Dec. 2000, doi: 10.1111/j.1813-6982.2000.tb01274.x.

[8] L. M. English and J. Guthrie, “State Audit of Public Private Partnerships in Australia: A Lack of Public Accountability?,” SSRN Electronic Journal, 2006, doi: 10.2139/ssrn.1361284.

[9] A. P. C. Chan and E. Cheung, “Fundamentals and features of public–private partnership,” Public-Private Partnerships in International Construction, pp. 3–16, Jan. 2014, doi: 10.4324/9780203736661-2.

[10] M. Ahadzi and G. Bowles, “Public–private partnerships and contract negotiations: an empirical study,” Construction Management and Economics, vol. 22, no. 9, pp. 967–978, Nov. 2004, doi: 10.1080/0144619042000241471.

[11] F. C. Fourie and P. Burger, “FISCAL IMPLICATIONS OF PUBLIC-PRIVATE PARTNERSHIPS (PPPs),” South African Journal of Economics, vol. 69, no. 1, pp. 147–168, Jul. 2005, doi: 10.1111/j.1813-6982.2001.tb00006.x.

[12] Matsumoto, C. et al, Mastering the Risky Business of Public-Private Partnerships in Infrastructure, 2021(010), pp. 61, https://doi.org/https://doi.org/10.5089/9781513576565.087.A000.

[13] G. A. Hodge, “The risky business of public-private partnerships,” Australian Journal of Public Administration, vol. 63, no. 4, pp. 37–49, Dec. 2004, doi: 10.1111/j.1467-8500.2004.00400.x.

COMPUTER VISION-BASED TILE COUNTING MODEL FOR AUTOMATED PROGRESS MONITORING

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Abstract

Construction industry in Korea has grown based on apartments. Tiles are installed in most of bathrooms of apartment houses so the numbers of tiles are huge to manage. Therefore, this paper proposes a computer vision-based model for automated tile counting. This model uses line detection and rectangle packing algorithm. The results of proposed model appeared that the average of accuracy in line detection and intersection points extraction stage is 98.8% with standard deviation of 1.2%. In calculation stage, the proposed model shows 90.1% of accuracy with standard deviation of 9.4% This implies model can solve the overcounting problem by quickly and accurately calculating the number of tiles with images acquired by the inspector's mobile phone in the field. Furthermore, it can contribute to creating a transparent construction industry.

Keywords: automated counting, computer vision, rectangular packing, tile work,

1. Introduction

Korea's housing type has grown based on apartments, and according to the Population and Housing Census [1] the number of houses nationwide as of 2021 was about 18.8 million, of which 11.94 million were apartments, accounting for 63.5% of the total. Based on this type of housing, Korea's construction industry has grown based on apartment buildings, especially focusing on high-rise apartments.

Most of the bathrooms in apartment houses in Korea are finished with tiles, which is one of the work types with the largest number of resource inputs. In general, since the size of the bathroom does not match the multiple of the standard tile, the corner part is finished with tiles be cut. These characteristics of the tile work make the conventional method of calculating with the human eye take a long time and produce inaccurate results such as overcounting the number of tiles used

Various studies have been conducted for automating the tile work. Wu et al [2] proposed a model to optimize floor tiles through BIM models at the design stage. Lin et al [3] proposed a model to investigate the alignment of tiles through computer vision. However, there are few research on the calculation of precise quantity of tiles including converting the nonstandard tiles to the standard tiles.

Therefore, this study proposes an automated model that counts the number of tiles during construction using computer vision. The proposed model are verified through the experimental study comparing the results by the proposed model and the manual calculation of the used tiles.

2. Literature Review

Computer vision, which belong to visual intelligence among artificial intelligence, is a field that enables computers to extract meaningful meaning from images like human eyes. With the remarkable progress of computer vision, automation technologies are being actively studied in various industries including the construction industry. In relation to earthworks, Kim et al [4] tried to interaction analysis through activity identification of earth moving excavator and dump truck. Yang Li et al [5] proposed real-time rebar counting through the YOLOv3 model. In particular, Hui et al [6] conducted a study of automated brick for façade in video frame, but there is limitation of not calculating the cut bricks as a complete brick that causes overcounting in progress estimation.

3. Methodology

3.1. Model Configuration

The characteristic of tile work is that 1) due to grouting work to fill the gap of tiles, square-shaped joints are inevitably formed for each tile. 2) There needs to be cut and install tiles on the edge of the remaining wall after attaching tiles. Using the characteristics of these tile works, each step of the model can be performed based on the joint line, and the validity of this model is verified through a method of calculating the number of uncut tiles using cut tiles. The overall flow of the proposed model is shown in Figure 1.

The proposed model proceeds from the tile-constructed wall picture to 1) line detection, 2) intersection points extraction, and 3) calculation.

3.2. Line Detection

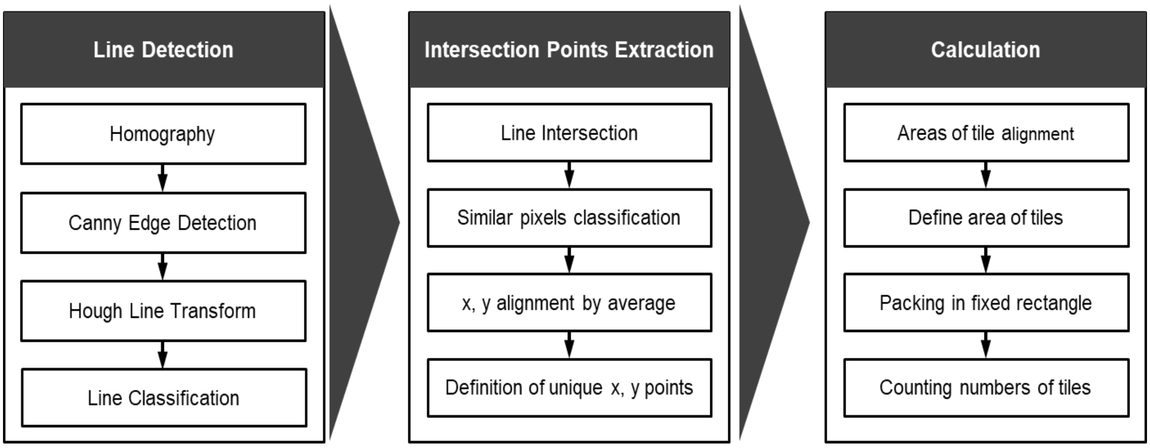

Fig. 1. Overall flowchart of proposed model

In the Line detection stage, the area of the tile can be distorted by perspective if the picture of the inspector is not taken from the front, so the area distortion of the tile is minimized by flattening the picture through the homography algorithm [7]. The method of the homography algorithm is as follows. In order to homography the image, the process of defining the four vertices of the square must be preceded, and when specified by the performer, a conversion matrix is generated based on this, and it acts on each pixel and spreads it in the forward direction.

$$s\begin{bmatrix}x'\\y'\\z'\end{bmatrix} = H\begin{bmatrix}x\\y\\z\end{bmatrix} = \begin{bmatrix}h_{11} & h_{12} & h_{13}\\h_{21} & h_{22} & h_{23}\\h_{31} & h_{32} & h_{33}\end{bmatrix}\begin{bmatrix}x\\y\\1\end{bmatrix}$$

The edges of the joint are extracted using the canny edge algorithm from photos with corrected perspective through homography. At this time, since the color contrast between the joint line and the tile is high, the canny edge threshold value is set high. Line detection is performed for each tile joint through houghline transform through the extracted edge. The K-means clustering algorithm is used to divide the detected line into vertical and horizontal lines. K-means clustering has the disadvantage of not performing well if the number of clusters, that is, k-value, is not appropriate, but in the case of the line to be detected, it is fixed vertically and horizontally at 2. The formula of the k-mean algorithm is as follows.

$$\underset{S}{Argmin} = \sum_{i=1}^{k} \sum_{x_j \in S_i} \left| x_j - \mu_i \right|^2$$

3.3. Intersection Points Extraction

In the line detection step, the intersection of each vertical and horizontal line can be extracted through a line divided vertically and horizontally. However, even in the Hough Line Detection stage, several lines are detected according to the Canny Edge threshold value, so several intersections may occur where each joint meets. In order to unify the x coordinates into one, the average of the intersections generated based on the vertical line was sorted, and the average of the y coordinates generated in the same way was also unified.

Table 1. Pseudo Code of algorithm for Intersection Points Extraction

Algorithm for Intersection Points Extraction
1. Create an empty list to store intersection points
2. For each vertical line and each horizontal line, calculate the intersection point:
3. Add the intersection point to the list
4. Return the list of intersection points

3.4. Calculation

In order to count the number of tiles, the area of the tile is defined based on the number of pixels based on the intersection points sorted by the average value. By sorting the areas in descending order, define the largest and repeated area among the calculated list of areas as the area of the tiles. However, when the number of tiles is counted by the area of the nonstandard tile on the edge, there is a problem that the number of tiles is calculated while ignoring the rectangular shape, the most important feature of the tile. To solve this problem, we used a rectangular packaging algorithm to package non-standard tiles into fixed rectangles defined by area tiles to maintain rectangular characteristics of tiles such as length and width. The pseudo code, written with reference to Jukka's algorithm [8] is as follows.

Table 2. Pseudo Code of Calculation using rectangle packing algorithm

Algorithm for Tile Packing Calculation
1. Sort the sizes of tiles in descending order.
2. Define the size of the largest and most frequent tile as standard size.
3. Initialize an empty bin list as standard tile size.
4. Sort height and width of non-standard tiles in descending order.
5. Insert the first rectangle into it.
6. For each subsequent rectangle
a. Iterate over the bins to find the first bin that can accommodate the rectangle.
b. If such a bin is found, insert the rectangle into it.
c. If no bin can accommodate the rectangle, create a new bin and insert the rectangle into it.
7. Output the list of bins.

4. Result

In order to verify the validity of the model, we compared the number which counted based on the actual length of the tile with calculated number of tiles through the model. The types of tiles to be tested were stacked bonds, monochrome, and subway tiles that are commonly used in bathroom in apartment buildings. In order to measure the effectiveness of line detection and Intersection points extraction algorithm, the percentage error of the area using the coordinates of the pixels of the intersection points was calculated. In order to verify the proposed model, the tile counting results by the proposed model are compared to the ground true by the human eye.

We tested total 30 pictures. The results shows that the average of accuracy in line detection and intersection points extraction algorithm is 98.8% with standard deviation of 1.2%. The proposed counting model shows the average of accuracy of 90.1% with standard deviation of 9.4% (Table 3).

Table 3. Test results

	Average	Standard Deviation
Line detection & Intersection points extraction	98.8%	1.2%
Calculation	90.1%	9.4%

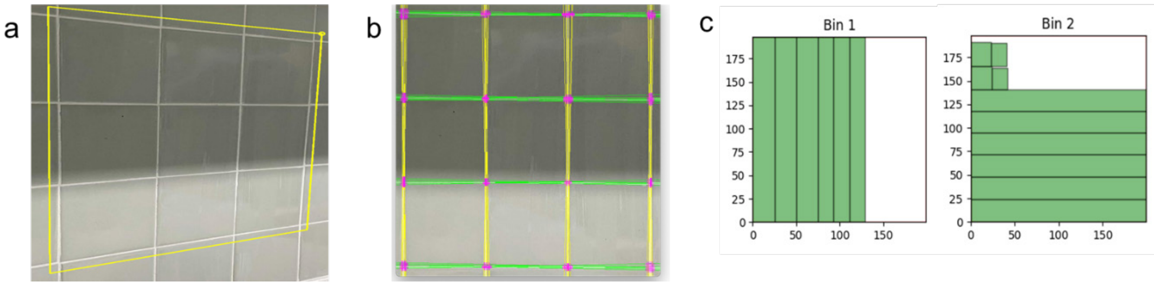

Fig. 1. (a) vertices performed by inspector; (b) intersection points extraction; (c) calculation

5. Conclusion

This paper proposed computer vision based tile counting model. The proposed model determined the number of tiles by specifying four vertices in the inspector's picture, correcting perspective, and packing the nonstandard tiles at the cut edge to the standard tile. As a result of the experiment in 30 pictures, the accuracy of line detection and intersection points extraction algorithm was 98.8% on average, and the tile counting model showed an average accuracy of 90.1%.

The results of this study can solve the overcounting problem by quickly and accurately calculating the number of tiles with images acquired by the inspector's mobile phone in the field. It can contribute to creating a transparent construction industry.

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References

[1] Korea Statistics, “POPULATION AND HOUSING CENSUS,” 2021.
[2] S. Wu, N. Zhang, X. Luo, and W.-Z. Lu, “Multi-objective optimization in floor tile planning: Coupling BIM and parametric design,” Automation in Construction, vol. 140, p. 104384, Aug. 2022, doi: 10.1016/j.autcon.2022.104384.

[3] K.-L. Lin and J.-L. Fang, “Applications of computer vision on tile alignment inspection,” Automation in Construction, vol. 35, pp. 562–567, Nov. 2013, doi: 10.1016/j.autcon.2013.01.009.
[4] J. Kim, S. Chi, and J. Seo, “Interaction analysis for vision-based activity identification of earthmoving excavators and dump trucks,” Automation in Construction, vol. 87, pp. 297–308, Mar. 2018, doi: 10.1016/j.autcon.2017.12.016.
[5] Y. Li, Y. Lu, and J. Chen, “A deep learning approach for real-time rebar counting on the construction site based on YOLOv3 detector,” Automation in Construction, vol. 124, p. 103602, Apr. 2021, doi: 10.1016/j.autcon.2021.103602.
[6] L. Hui, M. Park, and I. Brilakis, “Automated In-Placed Brick Counting for Façade Construction Progress Estimation,” Computing in Civil and Building Engineering (2014), Jun. 2014, doi: 10.1061/9780784413616.119.
[7] S. Benhimane and E. Malis, “Homography-based 2D Visual Tracking and Servoing,” The International Journal of Robotics Research, vol. 26, no. 7, pp. 661–676, Jul. 2007, doi: 10.1177/0278364907080252.
[8] Y. Zhou, J. Liu, R. Mandania, S. Li, K. Chen, and R. Xu, “Decision Support for Bundle Shipment Choices: Orthogonal Two-dimensional Bin Packing with Practical Constraints,” Proceedings of the 10th International Conference on Operations Research and Enterprise Systems, 2021, doi: 10.5220/0010221201610168.

CONSTRUCTION 4.0 MATURITY TOOL WITH ONTOLOGY DEVELOPMENT METHODOLOGY FOR ORGANISATIONS

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Abstract

In recent years the construction industry innovations have become an attractive market for investors. Innovations bring significant efficiency to construction companies while impacting business processes. Digital transformation in the construction industry is evolving slowly, as several criteria must be met simultaneously in order to be able to embrace these technologies for construction companies. In our research, we investigated which are the main pillars of the Construction 4.0 maturity model for organisations. As a result of our research, we created a Construction 4.0 organisational maturity model and verified the model by ontology development methodology. This model can help construction firms accelerate their digital transformation journey.

Peer-review under responsibility of the scientific committee of the Creative Construction Conference 2023.

Keywords: construction 4.0, digital transformation, maturity model, ontology, sustainability

1. Introduction

The value chain of the construction industry has undergone a digital transformation, resulting in the introduction of new technologies, methodologies, and concepts. This transformation has not only enhanced efficiency but also rendered the industry more sustainable, ultimately resulting in the creation of the Construction 4.0 ecosystem that refers to a cyber-physical ecosystem that incorporates various technologies, methodologies and processes aimed to create a human-centered sustainable construction industry.

The past two years have seen a growing number of construction companies taking substantial strides towards technological advancement as a result of the proliferation of digital technologies. Technological catch-up is further pushed by the recent availability of artificial intelligence to society. Yet the industry's adoption of technology-led business transformation has been comparatively sluggish due to management mindset [1], lack of IT knowledge, and limited process innovation that is necessary for the growing number of collaborating systems [2].

The slow pace of the Construction 4.0 transformation in the Construction Industry is attributed to insufficient education, unclear processes, and inadequately implemented technologies within the organisations. Providing strong external support can help companies navigate the digital transformation landscape and achieve optimal preparedness.

Based on the novelty of Construction 4.0 concept that has been emerged in the past three years no guiding framework has been introduced yet. Thus, the aim of this research is to improve a Construction 4.0 maturity model by building its ontology that guides construction industry organisations in order to assess and implement technologies.

2. Research methodology

Throughout this research, a combination of Design Science, Maturity model building and Ontology development were employed. The frame of the research was guided by Design Science Methodology which produces an artifact in the form of a model [3] that is widely used for maturity model building. Within the framework of maturity model building ontology development supports to logically clarify information's.

During the model building, we followed the six steps of the model building guideline proposed by de Bruin et al., 2005 as Figure 1 illustrates.

Figure 1 The Model Building Guideline

In the process of building the model, the initial step was to determine its scope. The primary objective of this model is to create an assessment tool for Construction 4.0 that enables construction companies to assess and enhance their business processes while supporting their digital transformation. The intended stakeholder for this model's development is academia.

The design phase was the second step in building the model. The main categories of the initial model and its subdomains were defined from literature review and the definition of Construction 4.0. The subdomains consist of industry-specific elements identified from our previous research. The primary driver for the application of the model will be internal requirements, and the respondents will be from the management level.

The populate phase is one of the most important parts of the model that defines what needs to be measured. It includes ontology building. Ontology is a "*formal and explicit specification of a shared (shared) conceptualization*" [5]. Ontology falls under the topic of knowledge representation within the field of artificial intelligence. It is one of the pillar of semantic technologies and knowledge-based decision support systems. The ontology development methodology provides a toolkit for mapping real-world objects, their characteristics and properties into a computer-interpretable form, thus enabling the development of artificial intelligence-based systems. However, ontologies not only encapsulate this conceptual model, but also describe more precisely the relationships between the elements of the model through axioms and rules, which by definition reflect the logic of the domain.

Figure 2 The Populate Phase - Ontology building steps

The populate phase was restructured with the ontology development approach (Figure 2). During our development process, prototypes and specific critical properties were formulated to determine the class membership. This was followed by a grammatically logical linking of the concepts, which was later combined into a complex set of ideas. The ontology thus constructed provides a description of the set of concepts of a domain. The ontology building includes seven steps: (1) defining scope and domain, (2) examining existing ontologies, (3) listing key terms, (4) defining classes and (5) class hierarchies, (6) defining properties of classes and (7) providing examples [6]. These steps can be done in a unified system using the Protégé software with the OWL2 Web Ontology Language, which has been developed by the University of Stanford for ontology machine processing. It includes the ontology built so far, which mainly helps to categorise the innovations.

3. The research – Building the formal model of the maturity tool

3.1. Scope

The impact of digitalisation in industrial manufacturing, Industry 4.0, has already led to the emergence of many of the technologies. Three years after the announcement of Industry 4.0, researchers found that organisations need strategic guidance and a holistic approach to integrate Industry 4.0 [7] to enable companies to effectively transform their business processes by considering risks and recognizing opportunities. A readiness assessment is "the systemic analysis of an organisation's ability to cope with and undertake a transformational process or change is defined as measuring or assessing readiness*"* [8]. Our long-term purpose is to develop a software to support technology implementation with giving advice.

3.2. Design phase: The Maturity Model

In 2019 defined five main dimensions: Manufacturing and Organisation, People Capability, Technology Driven Process, Digital support and Business Organisation strategy to evaluate SME's readiness for Industry 4.0 [9]. In a subsequent study, 18 maturity models were examined using nine criteria to enhance a comprehensive digital readiness model that can be applied to various contexts [10]. This research defined five main process dimensions: strategic governance, information and technology, digital process transformation and workforce management. At this stage of the research, we still accept that readiness and capability are equivalent and use them as synonyms, but later on we will emphasize the distinction between them.

The aim of this research was to create a tool for construction organisation to measure the organisational aspect of Construction 4.0. Thus, the first phase of this model building was to create the categories of Construction 4.0 within the organisation. Categories refer to the highest level of the model that defines the main Construction 4.0 aspects.

Six categories were identified as the initial point of the model from the literature review: Technology Management and Business Applications [9], Culture and People Management [9], [11]–[14], Collaboration and Communication [11], [14], Technology for Automation[9], [11], [14]–[16], Innovation [11], [14] and Change Management and Processes[9], [12], [14]–[16].

Technology Management and Business Applications refer to the process of planning, organizing, and controlling the use of technology within an organization to achieve its strategic goals and objectives. It involves the IT management of technology-related resources, including hardware, software, data, networks, and people and Cybersecurity.

Culture and People Management category pertain to overseeing the organizational framework, administering knowledge, and facilitating ongoing progress by means of digital leadership and persistent enhancement of skills among personnel within the organization.

Collaboration and Communication refer to the collaboration, communication and cooperation within the physical and digital environment of the organisation as well as throughout its supply chain.

The technology for Automation category includes the use of industry-specific automated devices, information modelling techniques, sensing systems and data infrastructure, AI and Machine learning and Human-machine interface to streamline and improve the efficiency of construction projects.

The **Innovation** category evaluates the corporate culture, leadership approach, and feasibility of innovation to foster the creation and implementation of novel concepts, products, services, technologies, or procedures that generate value, instigate beneficial transformations for the organization, and set it apart in the construction sector.

The **Change management and Process** category refers to the degree of alignment between organizational and digital processes that enable the company to promptly and efficiently address customer requirements, as well as to integrate or introduce new processes. This category also incorporates the organisational capability of change management.

These six lenses were selected to investigate the company maturity for technology adaptation. The literature review discovered that several common areas are in the maturity models meaning change management, people and culture, collaboration and so on [11]. Their main discrepancies are how these areas are emphasized, connected with each other and measured in these models. Our ultimate goal is to create a software that provides guidance for technology implementation, which necessitates the establishment of a rule-based system, hence we want to build an ontology-based system. The main advantage of the ontology development is to describe not just each category including its levels, but their relationships precisely for computer programs.

3.3. Populate phase: Ontology development

The Change Management and Process category was designated to illustrate how the ontology was built and serves what purposes. The ontology development put great emphasis on semantics of the concepts namely definitions, attributes, relations, axioms of classes [6]. The Change Management and Process category definition highlights

- specific processes such as organisational, digital processes, process integration and transformation. They share the common characteristics namely each process has set of tasks, use resources and are target oriented. In this sense, they are connected to the Process class as subclasses.
- the connection with change management whose importance was identified in many papers by [11]. The also stated that open and flexible organisational culture, leadership to conduct changes and shared learning among peers play pivotal role in enhancing change management. The characteristics of these concepts differ so they belong to other classes, but connected to the Change Management class through other relations (see Fig x). The light blue circles are related to the 'Change Management and Process category' view of the Maturity Model, the yellow ones are to the 'Information modelling techniques (BIM / Digital Twin)' below the 'Technology for automation'.

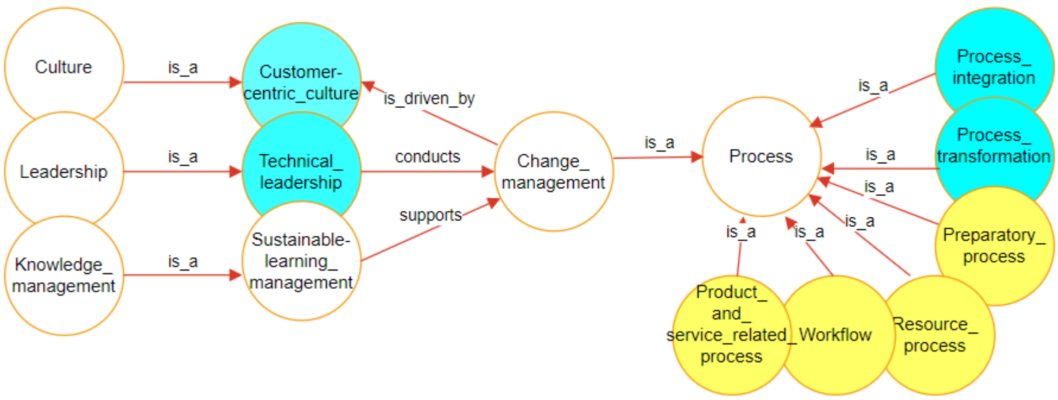

Figure 3 The Change Management and Process category

This model helps to design the questionnaire for detecting the company readiness for a given technology. It is worth noting that the measurement of customer-centric culture can differ in different countries due to the cultural aspects. Technical leadership is an ability so it can be measured by an ability test. Every process has input/output documents, so the existence of each process type can be detected by the specific documents. The model also presents that customer-centric culture is a driving factor of change management. The 'Culture and People Management' and the 'Process category' are connected via this link. If a change management is fully supported by a company with leadership and learning, but it is not customer-oriented, the technology implementation won't be complete. This is only an illustration how our rule-based computer program could give advice in a future in the respect of technology implementation. Once fully developed, the system can serve as a valuable tool not just for research and development, but also for industry to asses its Construction 4.0 capability and maturity.

3.3 Test phase: Case study of Kész Group

During the first test we verified the ontology thought a case study with KÉSZ Group from the construction of the Hungarian National Athletic Stadium where large volume metrology, BIM, DfMA, computer-controlled cable tension and parametric design was applied. During the test phase we explained each subcategory and its relation within the Change Management and Processes class.

Technical leadership was controlled by the company during the project and further consultancy company was involved. The combined use of these technologies required a **direct** guideline without which the company would not have been able to apply these technologies.

While assessing the **Process transformation**, it was determined that **proactive** change was required due to the implementation of a collaborative software system. The case study indicated that the processes and ecosystem used had already been implemented in a previous project, and thus, were deemed a proactive action.

The case study revealed that the innovations used to implement the complex project were generated by customer demand at the tender stage. The use of the innovations had to be defined by the company at the tender stage and was therefore assessed the **Customer-centric culture** as **proactive** behaviour.

Process integration has become an additional element of our model, as demonstrated in the case study. Some of the processes required by the technologies had to be **proactively** integrated or re-engineered into the company's existing processes.

4. Discussion and conclusion

The digital transformation of the Construction industry is a long journey in a complex environment, therefore, the key to achieving successful digitalization is to adopt a long-term strategy [17]. The purpose of research is to provide a guideline for creating this business strategy, and therefore contribute to the work of the research community.

The case study conducted during the model's testing phase revealed that the impact of technologies in each category manifests in construction companies through indirect, direct, or proactive activities. These findings will assist us in developing additional metrics for the maturity model.

We plan to continue our research by validating the entire model through qualitative and quantitative data. Additionally, we aim to establish measurable metrics, which can be used to develop a tool for market participants.

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References

[1] T. O. Osunsanmi, C. O. Aigbavboa, A. Emmanuel Oke, and M. Liphadzi, “Appraisal of stakeholders’ willingness to adopt construction 4.0 technologies for construction projects,” *Built Environment Project and Asset Management*, vol. 10, no. 4, pp. 547–565, Sep. 2020, doi: 10.1108/BEPAM-12-2018-0159.

[2] Ž. Turk, “Interoperability in construction – Mission impossible?,” *Developments in the Built Environment*, vol. 4, Nov. 2020, doi: 10.1016/j.dibe.2020.100018.

[3] A. Hevner, S. T. March, and J. Park, “Design Science in Information Systems Research,” 2004. [Online]. Available: https://www.researchgate.net/publication/201168946

[4] T. De Bruin, Q. Health, U. Kulkarni, and M. Rosemann, “Understanding the Main Phases of Developing a Maturity Assessment Model Exploring the Disruptive Potential of the Internet of Things View project Business Process Management in the Digital Age View project,” 2005. [Online]. Available: http://www.efqm.org/Default

[5] Thomas R.Gruber, “A translation approach to portable ontology specifications,” *Knowledge Acquisition*, vol. 5, no. 2, pp. 199–220, 1993.

[6] N. F. Noy and D. L. McGuinness, “A Guide to Creating Your First Ontology,” *Biomedical Informatics Reseach*, pp. 7–25, 2001, [Online]. Available: http://bmir.stanford.edu/file_asset/index.php/108/BMIR-2001-0880.pdf

[7] J. Ganzarain and N. Errasti, “Three stage maturity model in SME’s toward industry 4.0,” *Journal of Industrial Engineering and Management*, vol. 9, no. 5, p. 1119, Dec. 2016, doi: 10.3926/jiem.2073.

[8] F. Pirola, C. Cimini, and R. Pinto, “Digital readiness assessment of Italian SMEs: a case-study research,” *Journal of Manufacturing Technology Management*, vol. 31, no. 5, pp. 1045–1083, Nov. 2020, doi: 10.1108/JMTM-09-2018-0305.

[9] N. ’ Chonsawat and A. Sopadang, “The Development of the Maturity Model to evaluate the Smart SMEs 4.0 Readiness.”

[10] E. Gökalp and V. Martinez, “Digital transformation maturity assessment: development of the digital transformation capability maturity model,” *Int J Prod Res*, 2021, doi: 10.1080/00207543.2021.1991020.

[11] P. Das, S. Perera, S. Senaratne, and R. Osei-Kyei, “Paving the way for industry 4.0 maturity of construction enterprises: a state of the art review,” *Engineering, Construction and Architectural Management*, 2022, doi: 10.1108/ECAM-11-2021-1001.

[12] M. Bou Hatoum, H. Nassereddine, and F. Badurdeen, “Towards a Canvas for Construction 4.0 Implementation in AECO Organizations,” no. July, pp. 214–220, 2022, doi: 10.3311/ccc2022-028.

[13] B. Wernicke, L. Stehn, A. A. Sezer, and M. Thunberg, “Introduction of a digital maturity assessment framework for construction site operations,” *International Journal of Construction Management*, 2021, doi: 10.1080/15623599.2021.1943629.

[14] P. Das, S. Perera, S. Senaratne, and R. Osei-Kyei, “A smart modern construction enterprise maturity model for business scenarios leading to Industry 4.0,” *Smart and Sustainable Built Environment*, 2023, doi: 10.1108/sasbe-09-2022-0205.

[15] B. Succar, W. Sher, and A. Williams, “Measuring BIM performance: Five metrics,” *Architectural Engineering and Design Management*, vol. 8, no. 2, pp. 120–142, Aug. 2012, doi: 10.1080/17452007.2012.659506.

[16] Ž. Turk and na, “Structured analysis of ICT adoption in the European construction industry,” *International Journal of Construction Management*, 2021, doi: 10.1080/15623599.2021.1925396.

[17] T. Dolla, K. Jain, and V. S. Kumar Delhi, “Strategies for digital transformation in construction projects: stakeholders’ perceptions and actor dynamics for Industry 4.0,” *Journal of Information Technology in Construction*, vol. 28, pp. 151–175, Feb. 2023, doi: 10.36680/j.itcon.2023.008.

DEVELOPMENT OF A "PROJECT OBJECTIVE SYSTEM" (POS) TO ALIGN THE INTERESTS OF ALL THE STAKEHOLDERS AND FIND THE RIGHT DELIVERY MODEL

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Abstract

Major projects often exceed estimated costs and schedule. Therefore, they do not achieve the desired quality. The difference in objective interests of the project participants is a major problem. Based on the difficult contractual relationship. Also, the late involvement of subcontractors brings a lack of information for all involved with it. This lack can be described by the principal agency theory from the economic field. The current project execution models do not have a smart objective system that records the interests of the client from the start to the end of the project. They are neither documented at the start of the project nor adapted iteratively. With the help of the recently created project objective system (POS), the objectives of all project stakeholders can be selected, checked, and compared. Later on in the project procedure, the objectives will be transferred into risks. To know these risks and set the priority further on with the objectives. And the best fitting project delivery model can be chosen. The probability of successful project completion is much higher. Later, with the risk mitigation the objectives can be complied more efficiently. However the risk profile of the project and the risk aversion of the owner, decide on the delivery model. As a result of the POS with risk profile, for a very complex construction project the Integrated Project Delivery (IPD) with a cost-plus incentive fee contract would be the fitting model. IPD with the contractual relationship, the early involvement of all the participants creates understanding of the project early on. This can reduce information losses and risks. With the POS the incentive contract can be created and thus an incentive mechanism developed. In addition, the project delivery on time and within the budget is strongly supported. The POS is a software app for better usability.

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Keywords: cost- and risk management, delivery model, Integrated project delivery (IPD), principal agency theory, project objective system (POS).

1. Introduction and Motivation

Most of the time owners have to make decisions at an early stage of the project. At this time, the project is very unspecific. Goals and objectives are not clear or not well-defined. However, they need to be defined. An early defintion of the objectives enables the right choice for the delivery model can. In the late stages of the project only the perspective of the owner and stakeholders is relevant. Tosupport the owner, especially the public client,the Project Objective System (POS) will help to find the best solution for the specific project, all stakeholders and later on all participants. The focus of this paper is to develop a POS for owners to find the right delivery model and design the contract.

2. Theoretical background from the economics

In the economics, there are many theoretical descriptions for the contractual relationship. To design a software tool that should find the right delivery model and contract. This theories help to better understand the different realitionships and design the POS.

2.1. Essential theories for the contractual design and describe a system

The essentials theories to describe the contractual relationship and for the development a decision-based software toolcan be separated in five categories: Cybernetics, New Institutional Economic, Game Theory, Organization Theory and Control Theory.

2.2. Short breakdown of the needed information on Theories

Cybernetics is an interdisciplinary field that describes the communication and control mechanisms in complex systems and also the role of information processing, feedback, and organization [1]. Systems Theory is a holistic approach to understanding complex phenomena, where a system is viewed as a set of interconnected and interdependent parts that interact with each other and their environment to produce emergent properties and behaviors [2]. The New Institutional Economics (NIE) The new institutional economics (NIE) is a collective term from economics. It summarises various sub-approaches and gains in importance in joint consideration with business administration (BA) [3]. A part of the NIE is the Principal Agency Theory. It’s a framework that describes the relationship between two parties, where the principal hires an agent to perform a task. To align interests and reduce conflicts, incentives are used.[4]. The Transaction Cost Theory represents the cost of economic transactions, including the cost of searching for information, bargaining and enforcing contracts. This can have a significant impact on the behavior and efficiency [5]. There is no commonly accepted definition of the Theory of Incomplete Contracts. But it could be described as a suggestionthat not all possible contingencies can be anticipated and covered in a contract and that the allocation of control rights between parties. So there are always uncertainties [6]. Another part of this theory is the hold-up problem. It refers to a situation where one party makes a sunk, relationship-specific investment and then engages in bargaining with an economic trading partner [7]. Also, the Game Theory describes a relationship between two participants. It’s a framework for analyzing interactions between rational decision-makers, where the outcome of a decision depends on the choices of all the players which are involved [8] Organization Theory is firm through its structure, processes, and behavior of organizations, also including how they are designed, managed, and adapted to changing environments [9]. Another part of it is the theory of incentive concerned with the problem that a principal faces when his own objectives do not coincide with those of the other member. This problem can be fixed by an incentive [10]. Control Theory is an area of application-oriented mathematics. It’s theoretical framework examines how systems can be regulated and stabilized through feedback mechanisms that monitor and adjust their behavior, aiming to maintain a desired state or goal [11].

2.3. Conclusion of the Theories

The Theories or all important for developing a System and also for understanding the contractual relationship between the participants better. So to align the interests of the participants' incentive contracts can be used [12, 13]. Also, controlling (monitoring and reporting) is important [14, 15]. However, a contract is from the economical few always incomplete.

3. From the Project Goal to the Delivery Model

At the start of a project the owner has to set the project goals and, later on, the objectives [16] There are many definitions of the term "project goal and objective". In the following discussion, the definition of the International Project Management Association (IPMA) Competence Baseline (ICB 3.0) is used as a reference [17]:"*The project goal is to provide value to the interested parties. A Project strategy is a high-level view of how to attain the project goal. The project objective is to produce the agreed end results, especially the deliverables, in the time-frame required, within budget and within acceptable parameters of risk. The project objectives are the set of targets that the project, program and portfolio managers should attain to provide the expected project benefits to the interested parties."* So, a project goal is an achievable outcome that is broad and long-term. The project objective is a specific and smaller task that serves a broader goal. Since project goals and objectives are defined at the initiation stage, they are an important instance of making project success or failure measurable. For this reason, the goals and objectives should be formulated clearly and unambiguously. After defining the project goals and objectives in the later planning during the construction phase the goals and objectives will be transformed into a risk. So, it depends on the know-how of the owner, the status of planning (also the complexity and so on), and the risk that will incurre which delivery model and contract is best to find the right project organization form. So it is the priority to safe the project goals and to reduce the autonomy of the builder. Therefore, a cost-plus-fee contract which a Key Performance Indicator (KPI) model is much better. Especially complex project incentive contracts can be used to transfer the goal system of the owner to contractor. The owner can set incentives for every goal or objective.

4. Traditional and Innovative delivery model also Public Private Partnership

A Delivery Model is a model where the design, procurement, and construction of the project is managed. The choice of the right delivery model can have a significant impact.

4.1. Traditional Delivery Model and Innovative Delivery Model

In literature, there is no clear separation between the traditional delivery models and others. But most of the time the traditional models have bilateral contracts and hierarchical structures. In this paper the following delivery models are defined as traditional: Design-Bid-Build, Design-Build, Construction Management, Engineer-Procure-Construct (EPC) [18]. There are many more upcoming.

Because of cost overruns in different countries, the construction industry tried to create new delivery models [19]. Resulting in a lot of literature, analyzing and identifying the characteristics of the multiple “new” delivery models [20–24]. Futher on the delivery models will be defined as innovative delivery models. [25]

4.2. Public Private Partnership (PPP)

Public Private Partnership (PPP) is a long-term contractual agreement between a public agency (federal, state, or local) and another private-sector entity [26],[27]. The contractual arrangements try to improve public services by capturing the benefits of private-sector involvement [26].

4.3. Conclusion and demarcation

Table 1 is the conclusion and demarcation of the different delivery models and PPP. sTHe conclusion is, that if you want to transfer the risk of the operation time, PPP is fitting best. If you are at an early stage of a project and the planning level is very low, you use better an innovative delivery mode. The Traditional Delivery Model fits best by detailed planning.

Table 1 Traditional, innovative and Public Private Partnership [28, 29]

	Traditional Delivery Model	**Innovative Delivery Model**	**Public Private Partnership**
Type	Transactional	Relational	Relational
Team structure	Hierarchical	Flat	Flat
Contracts	Separate contracts Setup detailing how to sue and claim for compensation	Interlocking contracts Legally: direct and bind team activity Eliminate and reduce the ability to sue and claim compensation	Concessional contract, transfer the project from the owner to the construction company with the option to transfer it later back
Risk and reward	Risk is primary allocated Reward payment is based on delivery	Risk is primary shared Reward: pooled profit distribution is based on team success in achieving project goal Owner pays for additional extras	Risk is transfer from the owner to the construction company

Decision control	Hierarchical	Joint decision making Major project decisions are taken by primary team members	public owner are involved in the strategic planning. At the begin a high decision control which get with realization lost
Process	Linear information	Cross sharing of information „Best for project" mentality	Cross sharing of information, with later getting lower information flow

5. Contracts in construction industry

In the construction industry, there are a lot of different kinds of contracts. The contracts can be separated into different categories: unit price, fixed price, and cost-plus contracts. At Table 2 the different contracts are listed. In the list is a short description, the field of application when it fits best, and the principal of risk to be mitigated.

Table 2. Contracts in construction industry (without Cost or Cost-Sharing and Time & Materials and more) [30–33]

Name	**Field of application**	**Risk to mitigated**
Firm-Fixed-Price (FFP)	Requirement is well defined. -Contractor are experienced in meeting it. -Market conditions are stable. -Financial risks are otherwise insignificant.	None Thus, the contractor assumes all cost risk.
Cost-Plus-Incentive-Fee (CPIF)	An objective relationship can be established between the fee and such measures of performance as actual costs, delivery dates, performance benchmarks, and the like.	Highly uncertain and speculative labor hours, labor mix, and/or material requirements (and other things) necessary to perform the contract. The owner assumes the risks inherent in the contract-benefiting if the actual cost is lower than the expected cost-losing if the work cannot be completed within the expected cost of performance.

6. Development of the Project Objective System (POS)

With the literature analysis and the analysing essential theories a deductive and inductive approach is used for developing the POS. That can be described as the concept of the Project Objective System. At Fig. 4 the flow can be seen. The figure shows, that, first of all, the goals have to be defined. After that, every goal needs an objective. In the later process of the project, the goals and objectives transfer into risks. As described previously, with a certain level of planning and the level of risk the right delivery model can be choosen. So, from the theories before you choose a model with a relational contract. For example, you can choose an innovative delivery model or a PPP. If the owner doesn't want to give the Operate-Phase to another company he better chooses an innovative delivery model. To save the specific project goals in this case, he better chooses a Cost-Plus-Incentive Fee contract. Down below, the incentive mechanism is described. The horizontal axis shows the potential final costs for the client, the vertical axis the compensation of the contractor. The light blue dashed line shows the owner/contractor share-ratio. In this example, the ratio was set at 50/50 across all areas. This means that if the target cost is undercut or exceeded, the deviation is split equally between the two partners. At point (1) shows the target cost and the target profit, which were defined in the contract. The point (2) shows a scenario at the end of the project in which the final cost is lower than the agreed target cost. Due to the lower final cost, the green dashed line shifts to the left. This can be achieved by, for example, increased efficiency, the use of new, innovative construction methods, etc. In this case, the contractor generates a bonus of 50% of the savings in addition to the target profit (increased profit). The remaining 50% of the savings goes to the client. The point (3) represents a negative scenario. In this case, the target cost is exceeded, resulting in a reduction in profit. The final cost (yellow dashed line) shifts to the right in the horizontal axis. This can be caused, for example, by poor work performance, errors in the execution of the work, construction defects, etc. In this case, the Contractor is charged a penalty of 50% of the overrun of the target cost. The Client also has to pay 50% of the overrun. Point (4) shows a further increase in the final costs. In this scenario, the contractor would not make a profit at the end of the project and would lose part of his overhead. If this happens, there is no incentive left for the contractor.

In the worst case, only the production cost is covered. The distribution density of the potential final cost from the project risk twin. The distribution contains all uncertainties from base cost, risks, and escalation (future price increase) based on the direct project cost. In the example in KPI, an underrun probability of 50% (P50) is selected for the target costs. This means that the target cost will be reduced with a probability of 50%.[25]

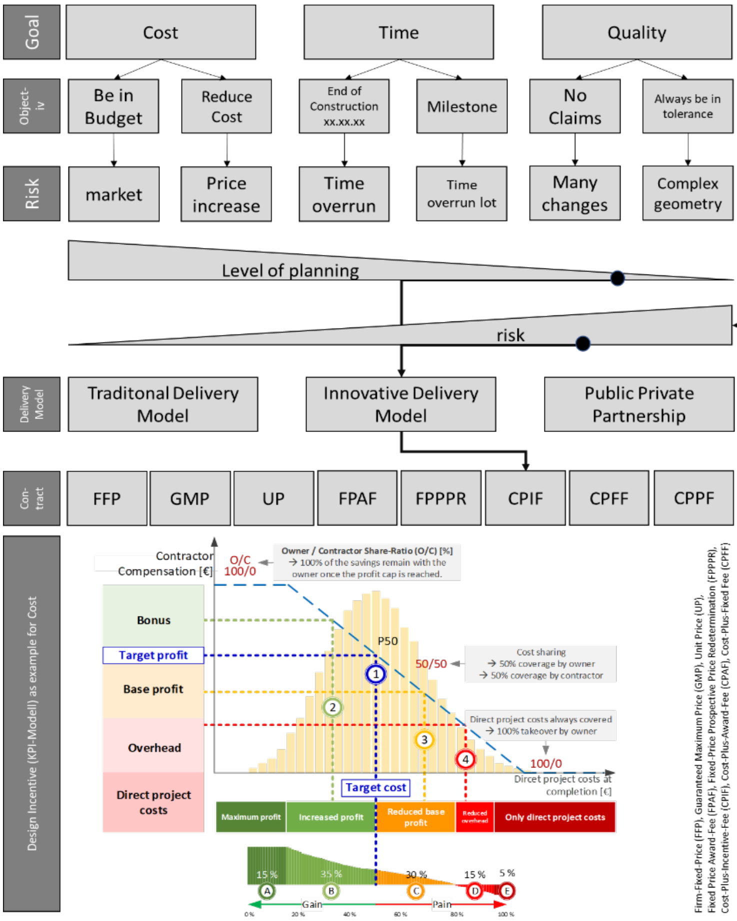

Fig. 1. From the Project Goal to the incentive mechanism

7. Conclusion and Outlook

The state of the research shows that there are some publications about finding the right delivery model and contract. Many of them choose the delivery model by qualitative evaluation. The praxis shows that owner in particular need the extern help of project managers to find the best fitting delivery model for thier project. Often it will be made a delivery report with a qualitative analysis. With a the risk approach, it is possible to make a quantitative choosing model.The previously shown POS is in development. In the next steps, the different kind of projects and their specific characteristic will be created. Also, the risk approach will be much more defined, and the creating of incentive mechanism is part of the process.

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References

[1] R. Cordeschi, „Cybernetics“ in The Blackwell Guide to the Philosophy of Computing and Information, L. Floridi, Hg., Oxford, UK: Blackwell Publishing Ltd, 2004, S. 186–196, doi: 10.1002/9780470757017.ch14.

[2] R. L. Jacobs, „System Theory and HRD“ in Handbook of human resource development, N. F. Chalofsky, Hg., 1 Aufl., Hoboken, NJ: Wiley, 2014, S. 21–39.
[3] C. Ménard und M. M. Shirley, Hg., Handbook of new institutional economics. New York NY: Harper an imprint of HarperCollinsPublishers; Springer, 2005.
[4] Dymski, Gary, A. und C. L. Kerstenetzky, „Global financial markets“ in Handbook of economics and ethics, J. Peil und I. van Staveren, Hg., Cheltenham: Elgar, 2009, S. 193–201.
[5] V. Grover und M. K. Malhotra, „Transaction cost framework in operations and supply chain management research: theory and measurement“, Journal of Operations Management, Jg. 21, Nr. 4, S. 457–473, 2003, doi: 10.1016/S0272-6963(03)00040-8.
[6] H. B. CHRISTENSEN, V. V. NIKOLAEV und R. WITTENBERG-MOERMAN, „Accounting Information in Financial Contracting: The Incomplete Contract Theory Perspective“, Journal of Accounting Research, Jg. 54, Nr. 2, S. 397–435, 2016, doi: 10.1111/1475-679X.12108.
[7] B. E. Hermalin und M. L. Katz, „Information and the hold-up problem“, The RAND Journal of Economics, Jg. 40, Nr. 3, S. 405–423, 2009, doi: 10.1111/j.1756-2171.2009.00071.x.
[8] Abdelhakim Hammoudi and Nabyla Daidj, „Game Theory and Strategic Management“ in Game Theory Approach to Managerial Strategies and Value Creation, A. Hammoudi und N. Daidj, Hg., Wiley, 2018, S. 1–25, doi: 10.1002/9781119419761.ch1.
[9] D. Warren und C. F. Miller, „Tools from Organization Theory“ in Value Maps, W. D. Miller, Hg., Hoboken, NJ, USA: John Wiley & Sons, Inc, 2012, S. 65–83, doi: 10.1002/9781119198222.ch4.
[10] J.-J. Laffont und E. Maskin, „The theory of incentives: an overview“ in Advances in Economic Theory, W. Hildenbrand, Hg., Cambridge University Press, 2013, S. 31–94, doi: 10.1017/CBO9781139052153.003.
[11] E. D. Sontag, Mathematical Control Theory: Deterministic Finite Dimensional Systems. New York, NY: Springer, 1998.
[12] M. Suprapto, H. L. Bakker, H. G. Mooi und M. J. Hertogh, „How do contract types and incentives matter to project performance?“, International Journal of Project Management, Jg. 34, Nr. 6, S. 1071–1087, 2016, doi: 10.1016/j.ijproman.2015.08.003.
[13] G. Stukart, „Contractual Incentives“, Journal of Construction Engineering and Management, S. 34–42, 1984.
[14] D. H. Guston, „Principal-agent theory and the structure of science policy“, Science and Public Policy, S. 229–240, 1996.
[15] R. Strauz, „Delegation of Monitoring in a Principal-Agent Relationship“, Oxford Journals, Nr. 3, S. 337–357, 1997.
[16] N. Simon, „Entwicklung eines Prämiensystems zur Berücksichtigung der Bauprozessqualität in Bauverträgen“. Dissertation, Universität Kassel; kassel university press, Kassel.
[17] International Project Management Association, ICB: IPMA competence baseline ; Version 3.0. Nijkerk: IPMA, 2006.
[18] M. A. El-Reedy, Construction Management for Industrial Projects: A modular guide for project managers. Hoboken, N.J: Scrivener Pub, 2011.
[19] S. C. Becker und H. Roman-Müller, Integrierte Projektabwicklung (IPA). Wiesbaden: Springer Fachmedien, 2022.
[20] I. González-Boubeta und J. C. Prado-Prado, „Integrated Project Delivery: A Literature Review and Research Agenda“ in Advances in Engineering Networks, R. de Castro und G. Giménez, Hg., Cham: Springer International Publishing, 2020, S. 11–18.
[21] S. Haghsheno, C. Baier, M. R.-D. Budau, A. Schilling Miguel, P. Talmon und L. Frantz, „Strukturierungsansatz für das Modell der Integrierten Projektabwicklung (IPA)/Structuring approach for Integrated Project Delivery“, Bauingenieur, Jg. 97, Nr. 03, S. 63–76, 2022, doi: 10.37544/0005-6650-2022-03-47.
[22] J. Warda, Die Realisierbarkeit von Allianzverträgen im deutschen Vertragsrecht: Eine rechtsvergleichende Untersuchung am Beispiel von Project Partnering, Project Alliancing und Integrated Project Delivery, 1. Aufl. Baden-Baden: Nomos Verlagsgesellschaft, 2020. [Online]. Verfügbar unter: https://ebookcentral.proquest.com/lib/kxp/detail.action?docID=6405419
[23] J. F. Yeung, A. P. Chan und D. W. Chan, „The definition of alliancing in construction as a Wittgenstein family-resemblance concept“, International Journal of Project Management, Jg. 25, Nr. 3, S. 219–231, 2007, doi: 10.1016/j.ijproman.2006.10.003.
[24] L. E. Bygballe und A. Swärd, „Collaborative Project Delivery Models and the Role of Routines in Institutionalizing Partnering“, Project Management Journal, Jg. 50, Nr. 2, S. 161–176, 2019, doi: 10.1177/8756972818820213.
[25] P. Sander, Becker, Simon Christian, Friedinger, Carl Philipp, S. Riemann, M. Ditandy und M. Spiegl, „Creating Incentive Mechanisms for Integrated Project Delivery“, tunnel, Nr. 4, S. 12–23, 2022.
[26] G. S. Kelley, Construction law: An introduction for engineers, architects, and contractors. Hoboken, N.J: John Wiley & Sons, 2012. [Online]. Verfügbar unter: https://onlinelibrary.wiley.com/doi/book/10.1002/9781118359150
[27] L. Ma, J. Li, R. Jin und Y. Ke, „A Holistic Review of Public-Private Partnership Literature Published between 2008 and 2018“, Advances in Civil Engineering, Jg. 2019, S. 1–18, 2019, doi: 10.1155/2019/7094653.
[28] G. Adel, A. A. Ezzat und N. Harinarain, „Integrated Project Delivery (IPD): An Innoavative Approach for Achieving Sustainability in Construction Projects“ in Bd. 245, Construction in 5D: Deconstruction, Digitalization, Disruption, Disaster, Development, T. C. Haupt, M. Akinlolu, F. Simpeh, C. Amoah und Z. Armoed, Hg., Cham: Springer International Publishing, 2023, S. 195–209.
[29] G. Ballard und G. Howell, „Lean project management“, Building Research & Information, Jg. 31, Nr. 2, S. 119–133, 2003, doi: 10.1080/09613210301997.
[30] H. Kerzner, Projektmanagement: Ein systemorientierter Ansatz zur Planung und Steuerung, 1. Aufl. Bonn: mitp-Verl., 2003.
[31] S. C. Becker, „Identifizierung von Anreizen in Verträgen nach der VOB/A-EU unter Einbezug von der VOB/B“ in Tagungsband zum 31. BBB-Assistent:innentreffen Innsbruck 2022, 2022, 16-29.
[32] American Institute of Certified Public Accountants, Audit and accounting guide: Construction contractors. Durham, N.C.: AICPA, 2019.
[33] Air Force Netcents, „Comparison of Major Contract Types“. [Online]. Verfügbar unter: https://www.netcents.af.mil/Portals/30/documents/NETCENTS-1/Documents/GenInfo-Comparison%20of%20Major%20Cont%20Types%202008%20Version%20Fina.pdf?ver=2016-08-03-154726-313

EFFECT OF BUILDING INFORMATION MODELING(BIM) INNOVATION ON QUANTITY SURVEYING

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Abstract

Quantity surveyors (QS) have various roles in the construction industry. One of their main roles is preparing bills of quantities that mainly entails taking measurements and pricing of construction work. They also develop schedule of project work, engage in construction project management, arbitration and dispute resolutions. Quantity take-off was their original role during 1820s when the profession was conceived. Critical observations brought criticisms alluding to the inability of the profession to survive if a tool could be developed that substituted QS roles in construction. Contingent to that criticism has seen the emergence of Building Information Modeling (BIM) that has specific attributes where the BIM technology can be used to quantify building works and produce schedule of works in 5D model interface. Thus far, has the BIM technological innovation posed threats to the QS roles and/or to the profession? The aim of this research was to investigate the effect of BIM innovation in the construction industry and to evaluate its effect on the quantity surveying profession. Is it a bane or boon to the QS profession? Specific objectives were to determine the extent of BIM usage by QS, the magnitude of relationship between the current BIM usage and the future of QS considering BIM growth in the construction field. Strength, Weakness, Opportunity and Threat (SWOT) analysis was conducted about BIM usage. Survey questionnaire was administered to investigate the effect of BIM, current usage and future standing in construction. The results showed that BIM was an opportunity that added to the progress of QS. It was concluded that QS needed to embrace BIM technology more with integration of digital twins for full benefit in the construction industry.

Keywords: building information modeling (BIM), construction industry, estimating, project management, quantity surveying.

1. Introduction

The profession of quantity surveying is important in the construction industry as it is involved in project cost estimates, cost control and overall project management. Quantity surveyor (QS) is the construction professional charged with these roles in the construction industry and they are from design phase, construction to maintenance and operation phase of a project; even to the demolition or deconstruction stage in the life cycle of a project. In some cases, they can be owner's representative in projects. Alhasan et al. (2019) stated that the quantity surveyor is one who on behalf of the employer is professionally trained, qualified and experienced in dealing with issues of construction costs, construction management and communication issues. The QS has different names in different regions globally. They are called cost engineers in the USA, building economists in some parts of Africa, Asia and UK, and their roles in projects have been developing over the years (Wao and Flood, 2016).

QS is found to have evolved overtime since its inception in 1820s where their main roles were taking measurements of work (Wao, 2015). This used to be manual and relied on 2D drawings to calculate quantities of work and to prepare bills of quantities (BOQ) as part of contract documents. At some point in the continuum, it was thought that any tool that would arise to better calculate and measure work would be a threat to the QS profession and render it obsolete in the construction industry (Wao, 2015).

With the increasing demands of project owners and position in the construction industry, QS has taken many roles such as cost planning, measurement and quantifying construction work, cost control throughout the project life cycle, financial advice and management, offering procurement advice to clients, etc., (Gilchrist et al., 2021). As noted by Fung et al. (2014), these services can be tedious, erroneous and inefficient especially if they involve a lot of information especially in large projects. Thus, QS had to find ways to keep up with the developments and maintain relevance in the industry.

The information technology (IT) and effective communication have provided opportunities for the QS. Their role of representing project owners and also acting as point of contact in projects as well as managing critical areas of project required them to improve. Areas such as Value Engineering (VE), Lean Management, Sustainable Construction, Building Information Modelling (BIM), Internet of Things (IOT), Digital Twins (DT), Artificial Intelligence (AI) and ChatGPT have been prevalent lately in various fields. These new areas have potential applications in the construction industry and QS can possibly use them as opportunities to improve and in marketing themselves. For example, research on BIM has shown that BIM has presented challenges and opportunities for the QS especially in the design stage of construction (Gilchrist 2021). Also, research showed that BIM is not a threat but rather an opportunity for QS to provide better value services and improved efficiency to project owners (Smith, 2014).

In spite of the viewpoints in favour of BIM use in construction, the implementation has been slow with some QS preferring to work with traditional methods to execute project work. Some have not embraced BIM as high cost of its implementation is hindering them from using it (Gilchrist et al., 2021).

Therefore, this research investigated the effect of BIM innovation in the current construction industry and to find if its effect was a bane or boon to the QS. There is research in this area but the IT area is ever fast changing and this can significantly affect the field in less time, and so this research informed prior research by assessing the QS field taking into consideration the current IT uses mainly BIM and DT. Literature review section assessed the QS profession in relation to integrating BIM and DT.

2. Literature review

2.1. Quantity surveyor in construction project

Quantity surveyor has key role of project execution in the construction industry. They oversee every aspect of the project right from preconstruction, construction to closeout, and also during operation, maintenance to deconstruction. The duties include quantity take-off, preparing bills of materials, scheduling of work, dispute resolution, project waste management, preparing bidding or tender documents as well as client/owner's representative in projects (Wao and Flood, 2016). The profession is popular in the UK, Africa, Asia and Australia where they have more responsibilities in projects beyond cost estimating as in the USA where they may be referred to as cost engineers, project estimators, cost manager or construction project accountant. Noteworthy, the Royal Institution of Chartered Surveyors (RICS) has popularized the QS profession with its chapters in the international arena through professional certifications and memberships (Wao and Flood, 2016; RICS, 2023).

The QS has had various challenges in providing their duties. These may include; other construction professionals competing with them for jobs in terms of services offered and fees, project owners increasing demands mounting pressure on them, perception that QS lack awareness for project value addition, and the current trends in construction such as sustainable construction and rapid technological advances which threaten to reduce QS roles (Gilchrist et al, 2021). Research on the challenges and avenues for QS to improve on project deliveries to remain relevant has shown that BIM is top in the opportunities (Alhasan, 2019; Wao, 2015). Professional organizations such as RICS have put competency requirements to improve on the value addition of QS in projects. RICS (2023) provide basic competencies which QS must meet such as having good understanding of professional practice and procedure, information and business skills, measurements and law. Core competencies such as quantifying and costing of building works by preparing BOQ, contracting and construction economics and preparing financial accounts for better project budget, are competences specific to improving QS. Optional competencies such as VE, risk management, BIM, research methods, arbitration and dispute resolution are areas of specialty and provide avenues for future career development and opportunities.

The influx of IT in construction has seen BIM as an area for continuous professional development (CPD) for QS. This has provided opportunities and strength in their value addition services (Wao, 2015).

2.2. Quantity surveying and building information modeling (BIM)

QS provides information about the project whether on procurement, cost, time, safety, or sustainability. These require providing information quickly for project success. This success depends on the QS in meeting the project goals efficiently. As noted by Alhasan (2019), the success criteria could be linked to time, cost, or quality which are key parameters for measuring project success over its life cycle.

The use of BIM by QS has been investigated as potential avenue to improve the productivity and efficiency of service delivery of QS. Wao (2015) study on predicting the future of QS in the construction industry noted that BIM had potential for being used largely by QS.

BIM is a collaborating process among construction teams where they exchange digital data of a project. That is, BIM is a technology and a set of processes to create, communicate and analyse building models in a way that is replicating what is to be constructed (Eastman et al., 2012). Those involved could be QS, engineers, architects, contractors, project owner, etc. BIM provides them with 3D modelling of the project and they could input cost in the model, hence called 4D, which is a cost loaded BIM 3D model. When time component is added, hence schedule, it becomes BIM 5D. Others from 6D to 9D could incorporate sustainability, facility management, lean management (for waste management), and safety. These can be integrated in 3D BIM. BIM can therefore greatly improve project quality by providing an overview of a project in a way that project data interchange is effectively communicated among teams.

With the IT BIM skills, the QS skills is expected to be improved in areas such as cost estimation, team communication, project management, etc. In this case, BIM usage by QS has been investigated especially in areas of estimation, quantity take off and planning where it has been stated that it can be a good value addition to provide accurate cost information through application of most effective quantity take off tools over the life cycle of a project (Alhasan et al., 2019). Even though this is an opportunity, BIM presents challenges especially early in the design stage. It has been noted that many QS are still behind in understanding BIM usage in projects and they are encouraged to embrace the technology if they want to reap the benefits. As noted by Alhasan et al. (2019), it is important that the project designs be detailed to replicate the actual project. It is obvious that BIM would not get accepted if the designers do not provide detailed digital information that is useful to the team over the project life cycle. As noted by Fung et al. (2014), there are several benefits of using BIM from preconstruction to post-construction during operation and maintenance periods, and these include speedy preparation of cost information at conceptual stage, providing initial cost data by extracting quantities from BIM models, generating cost information for different design alternatives, reducing design errors and cost revisions through clash detections, better 3D project visualization for improved design understanding, removing manual measurements and quantity take-offs, acting as project information management ,etc. These benefits can be avenues to market the QS with other professionals who maybe in competition with them (Wao and Flood, 2016). Noteworthy, BIM is a multi-dimensional construction tool that is promising to the QS since it can provide value addition to project owners. This promise is still farfetched because of lack of skilled personnel that understand BIM workflow, high cost of implementing BIM considering the high cost of hardware/software and related training and most importantly, lack of higher management or leadership support who are usually reluctant to embrace the technology (Gilchrist et al., 2021).

2.3. Building information modeling (BIM) and digital twins (DT)

Another area of IT that has been on the rise recently is the Digital Twins (DT) technology. BIM has been playing a key role in the design and construction stage of projects while DT which can be applied in the operation and maintenance phase of a project has the potential to shape a DT-enhanced BIM framework to fully enable whole life cycle digital/virtual construction (Honghong et al., 2023).

Digital twins refer to replication or digital mirror of the actual project which can mimic all aspects of the physical processes under the integration of the physical project details, virtual details as well as connection data between the physical and virtual project (Pan and Zhang, 2021). As stated by Pan and Zhang (2021), DT can combine BIM, Internet of Things (IoT) and data mining techniques whereby IoT connects the physical world and the internet/cyber world to capture real time data or information for building modelling and related analysis, and data mining methods incorporated in virtual building model is focused on discovering hidden knowledge in the collected data or information. This process can be done in the whole building life cycle, and so BIM based digital twins is a possible inclusion in the operation and maintenance of the construction world because it would be useful to see how the building operates in a virtual world and the construction team is able to identify errors and correct them before damages occur. This is why DT (initially proposed in 2003) was used by National Aeronautics and Space Administration (NASA) to simulate, forecast and evaluate spacecraft state with the aim of stopping potential dilapidation or failure of aircrafts. Just like lean management, VE and sustainable development, the concept of digital twins can be integrated in the construction industry to improve processes.

Pan and Zhang (2021) researched about building a data driven DT framework with BIM for advanced project management. Honghong et al. (2023) discovered that the adoption of DT in bridge engineering caused confusion which hindered the DT fusion to achieve its full capability and so their study focused on a DT enhanced BIM framework to shape full life cycle digital transformation for bridge engineering. And there could be other various ways by which BIM can be integrated with IoT and Artificial intelligence (AI); even with the current ChatGPT based on bot. Noteworthy, these studies show the value in integrated BIM-DT in projects but there is still lack of relationship between them. BIM has operational standards but not DT. This is an area for QS to venture into for full use of BIM-DT enhanced interface for improved project operations and maintenance. Therefore, this research focused on assessing BIM innovations and its effect to the QS profession. The following was the research methodology employed.

3. Research Methodology

This research set to investigate the effect of BIM innovation in the construction industry and to evaluate its effect to the QS profession. Is it a bane or boon to the QS profession? The specific objectives were to determine the extent of BIM usage by QS, the relationship between the current BIM usage and the future of QS considering the growth of BIM in the construction industry. Strength, Weakness, Opportunity and Threat (SWOT) analysis were conducted about BIM through literature reviews. Survey questionnaire was administered to explore the current BIM usage and future standing in the industry.

3.1. Survey questionnaire

Survey questionnaire was used to gather the views of the respondents about QS involvement in the construction industry and their ideas about BIM and DT. Emphasis was placed on their knowledge and use of these technologies in projects. The questionnaire consisted of multiple-choice and open-ended questions. A section of the questionnaire focused on demographic information such as work title, number of years in the field, being a project owner representative, role in projects, knowledge about BIM and DT and possible uses of these tools in projects, and their level of utilization in projects in terms of project budget. The other part required the respondents to rate their current level of satisfaction with using BIM in their projects/company on a five (5) point Likert scale (1 = not rewarding, 2 = neutral, 3 = somewhat rewarding, 4 = rewarding, 5 = very rewarding). In addition, they were asked their opinion about the overall growth in the usage of BIM in the next 10-15 years on a similar scale (1 = not improve, 2 = neutral, 3 = somewhat improve, 4 = improve, 5 = improve highly). Finally, they were to give reasons for the growth (or not).

3.2 Sample size and Data Synthesis

The study utilized 33 quantity surveyors who completed the survey. This sample size (n = 33) was considered adequate for statistical analyses and tests for adequate statistical power. SAS on Demand was used for quantitative data analysis which was mainly descriptive statistics. The descriptive statistical analysis results utilized the measures of central tendency that mainly comprised of mean/average values. The main purpose of the analysis was to determine the level of satisfaction with the current state of BIM use and to provide ideas for growth in future. Qualitative data were gleaned and assessed by content analysis.

4. Results and Discussion

Majority of the respondents were directors, senior quantity surveyors, senior cost managers, or professors. This shows that the sample was from a population that held leadership and managerial roles in construction. Out of the sample, 93% were males, 3% were females and 3% preferred not to say their gender. This outcome leads to a deduction that the QS field is male dominated and so it is important to encourage other genders to get into QS. The results also showed that about 90% of the respondents had over 10 years of experience, 72% had over 15years of experience with about 23% having over 30 years of experience and so it was prudent to conclude that they would provide invaluable ideas in regard to the BIM and construction industry. They were mainly involved in commercial construction projects (31%) and residential construction projects (26%) with industrial and heavy civil projects accounting for 19% and 11% respectively. About 62% had been project owner's representatives. Their roles included cost planning and control; contract administration; construction management; project management and integrative delivery partnerships; and consultancy. These roles aligned with those in the study by Wao and Flood (2016). About 97% of the respondents were registered with professional organizations and they mentioned that the benefits tied to those registrations and memberships were for idea/information sharing and networking, CPD, and being recognized as professionals by peers and institutions.

With regard to knowledge and familiarity with BIM, about 80% of respondents stated that they were familiar with the term with about 45% having first heard of BIM from reading while about 30% got to know BIM first from taking a course with about 15% hearing it first from job training. It can be concluded that avenues such as CPD and academics need to be used more to propagate BIM knowledge. Noteworthy, this familiarity and knowledge was not for long term use in projects. About 44% of the respondents had used BIM in their construction projects and from those who had used it in their projects, 70% of them had used BIM for about 2-5years with about 18% having used it for 6-10years and the rest (12%) having used it for less than 1 year. This states that BIM usage by QS was still in its infancy and needed to be embraced. For those who had used BIM in projects, about 53% had used it in 2-5 projects, 26% for 6-10 projects while 7% had it in over 20 projects. Again, this shows that a few embraced BIM.

Of those who had used BIM in projects, about 40% had used it in the design phase, 32% in the construction phase, 15% in facilities management and 4% in the deconstruction phase. Others (10%) used it in university training course. This implied that a few got involved with BIM training in the academia. Noteworthy, it was used in the facilities management and deconstruction phase which is an opportunity to integrate DT with BIM since DT is used more in the operation and maintenance phase.

When asked about the aspect of project they used BIM in, about 24% had used it in quantity take-off, 18% in estimating, 14% for 3D building simulation and clash detection respectively, 12% for scheduling, 6% for project presentation and 4% for waste management. The other (8%) had used it in sustainability. This shows that majority use BIM4D for QTO and estimating but also for the other extended versions like 5D, 6D to 9D which opens various applications and opportunities for QS. Also, about 26% of them used BIM in projects worth $2millions-10 millions, 12% in $51-100millions worth of projects with about 10% in projects over $100 million. In these projects, 89% of the respondents mentioned benefiting from using BIM. However, some experienced some difficulties in using BIM. They stated that BIM software were expensive with deep learning curve. This aligns with the literature review which stated that some of the hindrances to the BIM adoption by QS. Also, some cited getting 'buy in' from all the supply chain, information overload for some of the parties and too many revisions to drawings as some of the problems in BIM usage which also aligned with other viewpoints from the literature review. Also, some stated that there are few BIM operators which calls for more training of BIM professionals in the industry. A notable one stated that some design consultants fell behind with regular uploads of their developing models making them not able to be clash managed prior to tendering and this resulted in change management and additional costs post contract. This posed serious problems which should be addressed.

On the topic of digital twins, only 27% were familiar with DT. Of those familiar with it, 30% had heard about it from taking a course and from reading respectively while 10% from colleagues and from job training. When asked if they had used it in their projects, only 10% had used it. When asked if DT and BIM could be related, about 60% thought they were related. This provided opportunity for training on BIM and DT integration in construction. Majority of QS practitioners were not familiar with it, and so training and CPD, possibly by RICS, may have these put in the core or optional competencies for QS.

When asked about rating the current use of BIM in their companies, about 62% of the respondents thought that it was rewarding with about 27% being neutral and about 6% on the somewhat rewarding range while about 5% stated that it is not rewarding. Average score of 4 meant it was rewarding on a 5-point Likert scale. The same percent scores were seen when asked for the level of satisfaction with the current use of BIM in their companies with a mean score of 4 implying satisfied on a 5-point Likert scale.

For the growth in usage of BIM in projects in the next 10-15years, 70% believed that it would greatly improve, 10% were neutral while 20% thought it would somewhat improve. So about 90% of the respondents believed that BIM would be better in future and this could provide a great opportunity for QS. This aligned with Wao (2015) that also noted BIM for greater use in future. Some viewpoints of the respondents for future of BIM alluded to BIM evolving with great potential for improvement, more contracts requiring BIM uses and the fact that BIM was increasingly getting adopted in projects with more innovations and applications expected in years to come.

5. Conclusion

This research has used survey questionnaire to investigate the effect of BIM on QS profession and to determine the breadth of its current usage and future standing in construction. Strength, Weakness, Opportunity and Threat (SWOT) analysis was conducted on BIM. It was found that BIM had not been fully embraced within the QS field and the few who had embraced it had not employed full potential of BIM in projects. DT as integrated with BIM was also not popular in the QS field and was not applied fully in projects. As such, the QS field needed to integrate full use of these technologies to enhance their value addition in projects and also to develop professionally.

This research added into the body of knowledge that focused on the application of IT in the construction industry with special emphasis on BIM and DT. The use of BIM had shown that it was rewarding to the QS, and BIM was expected to improve in the next 10-15 years. Future research could focus on DT and its application in the construction industry especially in the operation, maintenance and deconstruction stage which focuses on closed loop system or circular economy and sustainable construction.

Reference

[1] Alhasan, Soleen, Omar Amoudi, Michael Tong, and Bimal Kumar, "Effectiveness of adopting BIM on quantity surveying profession during the project life cycle", In *THIRTY-FIFTH ANNUAL CONFERENCE*, p. 273-282, 2019.
[2] C. R. Gilchrist, R. Cumberlege, and C. Allen, “Lack of implementing Building Information Modelling in the quantity surveying profession,” IOP Conference Series: Earth and Environmental Science, vol. 654, no. 1, p. 012025, Feb. 2021, doi: 10.1088/1755-1315/654/1/012025.
[3] J. O. Wao and I. Flood, “The role of quantity surveyors in the international construction arena,” International Journal of Construction Management, vol. 16, no. 2, pp. 126–137, Feb. 2016, doi: 10.1080/15623599.2016.1142251.
[4] J.O. Wao, "Predicting the future of quantity surveying profession in the construction industry", Journal of Construction Project Management and Innovation vol. 5, no. 2, pp. 1211-1223, Dec. 2015): https://hdl.handle.net/10520/EJC183324
[5] Eastman, C Teicholz, P and Sacks, R., “*BIM Hand Book”* 2012, 2nd Edition. Chichester: J Wiley.
[6] P. Smith, “BIM & the 5D Project Cost Manager,” Procedia - Social and Behavioral Sciences, vol. 119, pp. 475–484, Mar. 2014, doi: 10.1016/j.sbspro.2014.03.053.
[7] “Royal Institution of Chartered Surveyors (RICS)”, https://www.rics.org/profession-standards (Access date: 05.18.2023)
[8] S. Honghong, Y. Gang, L. Haijiang, Z. Tian, and J. Annan, “Digital twin enhanced BIM to shape full life cycle digital transformation for bridge engineering,” Automation in Construction, vol. 147, p. 104736, Mar. 2023, doi: 10.1016/j.autcon.2022.104736.
[9] W. P. Fung, H. Salleh, and F. A. Mohd Rahim, “Capability of Building Information Modeling Application in Quantity Surveying Practice,” Journal of Surveying, Construction & Property, vol. 5, no. 1, pp. 1–13, Jun. 2014, doi: 10.22452/jscp/vol5no1.4.
[10] Y. Pan and L. Zhang, “A BIM-data mining integrated digital twin framework for advanced project management,” Automation in Construction, vol. 124, p. 103564, Apr. 2021, doi: 10.1016/j.autcon.2021.103564.

ENGINEERING WORKFORCE PLANNING AND WORKLOAD MANAGEMENT IN THE US ARMY CORPS OF ENGINEERING

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Abstract

Throughout the United States Army Corps of Engineers, the process of workforce planning and workload management remains a challenge. The purpose of this research was to understand the tools available to assist with these functions, determine how these functions have been performed in the past, collect best management practices from leaders in the organization and engineering industry, analyze current processes and limitations, understand impacts of the current working environment on planning and management, and identify ways to improve mission delivery, prevent employee burnout, and more evenly distribute workload. The researcher used qualitative methods, including literature review, action research, and semi-structured interviews, to perform the research. The responses provided during the interviews were analyzed to determine common themes – most critically, that there is no single tool identified that could perform both workforce and workload management functions and that all parties, whether part of USACE or private sector firms, were performing these tasks differently.

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Keywords: engineering, management, planning, workforce, workload

1. Introduction

The Office of Personnel Management (OPM) defines workforce planning as “the systematic process for identifying and addressing the gaps between the workforce of today and the human capital needs of tomorrow” [14]. See Figure 1. Workforce planning involves analyzing the makeup of an existing organization, determining future workload and requirements, and identifying areas for improvement (new hires, training, etc.) to enable mission success in the future. Workforce planning remains critical as it allows managers, leaders, and corporate executives the opportunity to evaluate the organization’s status versus where the organization may need to grow or change to successfully complete future work. It provides the time to strategically analyze not only how many employees an organization has, but also to examine the knowledge, skills and abilities possessed by the team in conjunction with the projected types of work or tasks to be completed in the future.

Figure 1 OPM’s Workforce Planning Model [14]

2. Research Background

To retain the most valuable resource in an organization, people, leaders are having to adapt and find new and creative ways to meet and exceed expectations of its employees. It is no longer enough to provide an employee a place of work and compensation, it is just as important to provide a quality workplace and ensure that the employees genuinely want to come to and enjoy their work. Since the COVID-19 pandemic, America has experienced a period known as the "Great Resignation." This era is defined as "an ongoing economic trend in which employees have voluntarily resigned from their jobs en masse, beginning in early 2021." Potential causes of this trend include safety concerns with working during the pandemic, increased cost of living without increased wages, lack of childcare due to schools and childcare facilities closures during the pandemic, and the desire for remote or telework positions [7].

As industry continues to rebound, managers and leaders must work to create optimal working conditions to ensure retainage of employees and minimize the need for personnel actions to backfill vacant positions. As resignations continue, managers are tasked with reshuffling workload, selecting, and onboarding new employees, often in a virtual setting. To prevent additional resignations, managers must determine the balance of distributing and managing the workload to execute the mission while ensuring employees are not overtasked to prevent burnout. In addition to multiple resignations across the enterprise, the USACE received a significant increase in workload due to two laws passed by the administration this year, the Infrastructure Investment and Jobs Act (IIJA) and the 2022 Disaster Relief Supplemental Appropriations Act (DRSAA). These two acts include more than $22.5 billion in additional projects for the agency [3]. With every distribution of funds from the two laws, the question remains the same – can the organization handle the amount of work presented?

3. Research Aim

The aim of this research is to investigate available tools for workforce planning and workload management to effectively and efficiently determine if an organization can execute additional projects while minimizing the occurrence of resource overload or employee burnout.

3.1 Objectives

1. Understand the tools available to assist with workload management and workforce planning and document best management practices
2. Analyze current processes and limitations
3. Understand how the current work environment has further affected the ability to plan
4. Identify methods of planning to improve mission delivery, prevent employee burnout, and more evenly distribute workload amongst the workforces

3.2 Key Questions

1. What is the most effective method of workload management and workforce planning?
2. Is there a tool available that not only allows workload and workforce planning but also workload management to include analysis of work performed or real-time earned value analysis?
3. How are managers scheduling projected workload in a constantly changing work environment that is affected by COVID-19?
4. How are leaders performing project prioritization when resources are limited or constrained?
5. How can managers most effectively forecast future workload to ensure the organization is resourced appropriately?

4. Literature Review

Workload management is defined as the "process of assigning tasks to keep the team working while monitoring progress over the course of [a] project" [19]. It is the task of distributing work or assignments amongst a team to complete a project, ensuring that the right resources are allocated and available when needed to perform. It also involves monitoring distribution of workload to avoid over- or under-utilizing resources and ensuring tasks are completed on schedule, within budget, and meeting or exceeding quality standards. With over 37,000 employees, the United States Army Corps of Engineers (USACE or enterprise) remains one of the world's largest public engineering, design, and construction management agencies [17]. With a $7.8 billion operating budget in 2021. With this magnitude of employees and subsequent volume of projects, workforce planning and workload management remain crucial components of the agency's success.

During the pandemic, telework became an essential part of the USACE organization to ensure continuity of duties in a socially distanced environment. Telework provided the flexibility needed to allow employees to log on from their homes, increased work-life balance, and provided an additional, temporary benefit of family caretaking while working. Government teleworkers exceeded expectations after initial proverbial roadblocks (limited virtual private network (VPN) access, learning curve for conducting virtual meetings, etc.) were cleared and statistics show increased productivity and job satisfaction since telework was authorized for the wider employee population. For those who have worked in a telework or remote work environment for the past two years, it is not something that most are willing to compromise on in their careers moving forward. It has become a valuable benefit for job seekers with “50% of employees want[ing] their next job to offer flexible working conditions” [10]. With the assistance of telework, the USACE has pivoted from a traditional cubicle/office organization to a more flexible, mostly hybrid working environment.

4.1 Shift in Age of Employees

Over time, the average age of the USACE employee group has decreased with around 25,000 (67.5%) employees over forty years of age and approximately 12,000 (32.4%) employees forty years of age or younger in 2019 as compared to just ten years ago, in 2012, where 77.3% of the workforce was forty or older. The agency’s demographics are starting to trend younger, and as such, the need for workforce planning and workload management is increasing to effectively manage transitions and project reassignments as the older population retires more frequently and positions are backfilled. It is also important to note that younger employees are more likely to resign from their federal positions than their older coworkers and the enterprise should evaluate all alternatives to ensure retainage, including improving the workforce planning and workload management process to ensure reduced risk of resignation due to stress or overload [11].

4.2 Influx of Work

The President’s Budget provided approximately $4.6 billion in fiscal year (FY) 2017 funding for the USACE civil works program. The President’s Budget for the current FY, 2022, included roughly $6.8 billion in funding for the USACE civil works program, an increase of over $2 billion in just five years. Along with increased funding from the President’s Budget, the USACE also received funding through the IIJA and DRSAA programs. These two acts provided more than $22.5 billion in additional funding for the agency in FY22. Overall, the enterprise is responsible for $29.3 billion of projects between the President’s Budget, IIJA, and DRSAA, not including military funding or other sources. This is over six times the budget received just five years ago. As most of this influx is temporary, the USACE is mostly planning to determine methods to execute the work with existing resources for the time being but to successfully execute this tremendous surge of work, planning must be conducted more diligently than in the past.

4.3 Current Job Market Conditions in Engineering

The construction industry was predicted to see the highest percentage in job growth (13%) from 2018-2028 when compared to all other industries in the United States. While the overall industry is expected to experience continued growth, there is a difference in compensation when comparing the pay of federal employees versus their private sector counterparts. This is debatable and subject to many variables, including locality, number of years’ experience, specialization in engineering, etc..., but one thing remains the same – the organization is experiencing loss of mid- to upper-level engineers to private sector companies who have the flexibility to compensate the employees at a higher level than what is attainable within the limits of the Office of Personnel Managment (OPM) General Schedule pay table. In the USACE, a typical early career engineer with licensure would be employed as a GS-12, starting at Step 1 with an annual salary of $68,299. If the location where the employee is working does not qualify for locality pay or other adjustments, this salary is almost $35,000 lower than the average annual salary for all engineering occupations.

Another item to consider is the resignation rate of the federal sector, which has gone from 0.2% in June 2009 to 0.7% as of November 2021. This translates to approximately 70 employees previously resigning to 245 employees currently exiting the USACE monthly. While this number seems relatively small in comparison to the overall number of USACE employees (35,000), it remains a concern. There are many factors that could be attributed to the increase in rate – COVID-19 and associated health concerns, childcare instability, and shift in how Americans feel about work but one way the industry can work to reduce this rate is to ensure fair distribution of work, better scheduling of tasks, and reduced stress as a result of improved planning [6].

4.4 Automated Information Systems (AIS)

The automated information system (AIS) mandated for use in the USACE project management community of practice is the Project Management Automated Information System (PROMIS or P2). P2 was created in 1988 and utilizes Oracle Primavera software for project scheduling. Oracle Primavera is a software developed by the Oracle Corporation that encompasses the total project management processes including "project management, scheduling, risk analysis, opportunity management, resource management, collaboration and control capabilities, and integrates with other enterprise software" ("Primavera (software)," 2022). P2 is a competent tool for workforce planning and workload management but it is limited to resourcing to the organization and is not easily utilized for resourcing to the individual employee.

Microsoft (MS) Project is utilized by project management at the Wilmington District to develop detailed schedules with milestones that flow into P2. MS Project is software that has been the most popular amongst project managers of all industries for years [12]. The program allows users to build schedules with tasks, durations, dependencies (predecessors and successors) as well as resourcing organizations or individuals. MS Project also produces a Gantt chart to allow for schedule visualization and, with the appropriate coding, can feed data into other applications such as P2, Power BI, or other data management and visualization tools. MS Project does require license purchasing but is a tool that a core group within the district are familiar with and know how to utilize and edit schedules. MS Project does not provide a summary of workload across a program without the use of a data visualization application, such as Power BI or Qlik Sense.

Excel spreadsheets are a more rudimentary software for scheduling but can still be effective in workforce planning and workload management. This tool can be used satisfactorily for smaller programs and projects but becomes ineffective and cumbersome for larger projects. (Windsor, n.d.) There are ways to format an Excel spreadsheet to create templates or add-ins to install to assist with building Gantt charts and simulating task predecessors, successors, and interdependencies, but there are other programs available that can perform these tasks with less manipulation. Another disadvantage with Excel is that it does not communicate with other USACE applications (P2, USACE financial management system (CEFMS), etc.) and therefore creates a duplicate schedule, introducing the potential for error. If a schedule is started in Excel, it can easily be imported into MS Project for additional formatting and organization [15]. Use of Excel does not require any additional licensing and is familiar to most within the organization but would be difficult to use for program-level analysis.

Engineering Management System (EMS) is a web application developed by the USACE in 2014 and is used by engineering staff to develop budgets, assign resources, build internal detailed schedules, monitor execution, and provide reports for analysis. This tool was specifically built to resource and analyze workload to the individual and was designed to complement P2 and other established USACE project management systems. EMS pulls data from the CEFMS and allows functional managers and project managers to quickly access project information and obtain real-time earned value and scheduling analyses. One of the drawbacks to EMS is that it does not interface with MS Project, so the USACE Wilmington District would need to replicate schedules created in MS Project in EMS. This effectively creates duplicate schedules within the district, introducing potential for error and additional workload when MS Project schedules are updated. EMS allows multiple users to edit budgets, schedules, and other components simultaneously, which allows for quicker development of products. It is also a no-cost tool, and no licenses are needed, making it one of the more cost-effective options.

Data Visualization Tools: Qlik Sense and Power BI are becoming more popular in resource management [18]. The ability to use data and tools to provide graphic representations of a project or program status is a new trend in the project management community of practice. Tools such as Qlik Sense and Power BI allow leaders and managers to prepare concise reports with real-time information to ensure accurate reporting and facilitate efficient decision-making when challenges arise. The USACE is utilizing both tools with Qlik Sense more widely used currently. Districts are working towards implementation of Power BI due to its ability to integrate with other systems and ease of use. (Team, 2019) Additional comparison of the two tools is illustrated in the chart below. While neither tool is the direct source for workforce planning and workload management, they are critical in creating the graphic visualizations needed to convey status of the workforce and project execution.

4.5 Practices to Improve Mission Delivery

Strategic agility, commitment to values and goals, vertical and horizontal alignment, and team diversity are all practices to improve mission delivery. There are ways that each of these practices could be supported in implementing a more detailed workforce planning and workload management process. In today's environment, it is more critical than ever for large organizations to maintain a sense of strategic agility. Strategic agility is defined by Harvard Business Review as "the ability to improve performance – not just survive but thrive – amid disruption" (Wade et al., 2021). In short, organizations must maintain some measure of fluidity, to be able to move from one project to another and the ability to move resources from one project to another as the situation calls. The same is true for the USACE. As projects are deferred, put on hold, or funded unexpectedly, the enterprise must remain agile to remain relevant and productive. One way to maintain this agility is to have a tool that allows for quick view of projects and programs, allowing for real-time scenario development – expansion of the "if/then" process – to better understand potential outcomes for different situations. For example, resource managers and leadership could game plan a scenario to show impacts to billable hours for employees if a district were to lose or gain a major project or determine how to re-assign resources to ensure all remained appropriately resourced in the event of a project loss.

Another practice to improve mission delivery is to have the team committed to shared values and goals. Introducing further detailed workforce planning and workload management could allow for all members of the team (resources, resource managers, project managers, district leadership, stakeholders, etc.) to visually see how the team plans to meet the shared goal of project execution and understand how the subject project may (or may not) impact other projects. This visibility could foster improved decision-making and workload prioritization. In turn, providing vertical (leadership) and horizontal (project delivery team) alignment to ensure a project's success. Having a fully resourced project schedule with buy-in from the team can go a long way in overall mission execution and is critical to ensuring the project gets the best start possible.

4.6 Burnout/Mental Health

In refining the workforce planning and workload management process, the USACE could recognize benefits from a mental health perspective. Mental health and stress remain one of the top sixteen reasons that two in five people are prepared to resign from their current employers in 2022 [1]. In fact, the current rate of resignation is at a 20-year high and does not appear to be decreasing any time soon [10]. In an organization like the USACE, where projects are executed within tight timelines, budgets, and are in support of important missions (national security, hydropower, navigation, and research and development to "protect the environment and enhance quality of life"), there is no surprise that mental health remains a focus of the enterprise [13]. Through shadowing multiple leaders throughout the enterprise in previous leadership development training, the author heard many confessions when they experienced burnout, the causes that led to it, and ways to avoid experiencing the feeling altogether. Burnout is defined as "a form of exhaustion caused by constantly feeling swamped. It is a result of excessive and prolonged emotional, physical, and mental stress. In many cases, burnout is related to one's job" [4]. Most often, feelings of having too much work to do and not enough resources or time to do it were leading causes of burn out. One way to reduce the potential of burnout is to perform more comprehensive planning to provide a better understanding of existing workload, projects, and resources. If there was a tool to provide a quick snapshot of an individual's workload, the first level supervisor could identify any issues, including over-resourcing, before they occurred and could either re-assign other team members to assist with the workload or pursue brokering the workload with another district to avoid the potential of burnout due to exhaustion.

4.6 Resource Leveling

Resource leveling is defined as the process of resolving a constraint when one resource is required to perform more than one task at a time. It is the process of resolving the conflict and usually comes at the expense of one of the traditional project constraints – scope, time, and cost [16]. Resource leveling, if performed correctly, can lead to reduced potential of resource overload, and allows reasonable expectations to be set at the onset of the project (proactive vs reactive management). If not performed, resource overload can occur and can lead to mistakes, inefficiencies, and breakdowns in overall mission execution [5]. A single tool to provide a quick snapshot of an organization's workload could allow more effective resource leveling, eliminating the "guess work" employed by first line supervisors. While previous literature highlights the importance of resource leveling, there is not sufficient published information to document how this occurs and methods to avoid overload in a matrix, multi-project organization like the USACE enterprise.

4.7 Retaining Talented Workforce

All the previously mentioned subtopics - practices to improve mission delivery, prevention of burnout, and resourcing leveling - are elements in retaining a talented workforce. In 2014, twenty percent of the USACE workforce was eligible for retirement with an additional twenty percent eligible for early retirement – that is a total of forty percent of the current workforce that could retire immediately [2]. Understanding the wealth of knowledge possessed by the forty percent of retirement or early retirement eligible employees, the USACE must find creative ways to not only attract new talent but also retain the current workforce. One of those ways is to provide a stable, predictable work environment with a healthy work-life balance. In utilizing a better tool and more effectively integrating technology to provide a more detailed approach to workforce and workload planning, the enterprise could ensure that the talented workforce currently onboard remains and potentially gain new employees by ensuring minimization of resource overload in addition to other recognized benefits (insurance, flexible working hours, performance awards, moving expenses, etc.) [8].

5. Reasearch Methodology

Semi-structured interviews are defined as "in-depth interviews where the respondents have to answer present open-ended questions…" [9]. Semi-structured interviews were selected as a method for this research to gain insight and knowledge regarding the current workforce planning and workload management process from leaders within the USACE's South Atlantic Division Engineering community accompanied by a brief demonstration of the tool developed as part of the action research. The intent of the interview was to gain insight from leaders and managers who are part of the process and to receive feedback on the tool for further refinement. The interviews were conducted via WebEx or teleconference.

6. Results

Questions established creditability of the interviewees and documented their level of experience to further understand their responses to the remaining questions. All interviewees are at the second level manager or higher-level leadership within their respective organizations with all having at least fifteen years of experience in engineering and management. Almost all interviewees, whether USACE employed or private sector employed, currently use Excel to some extent to perform workload planning and workforce management. Half of the interviewees are utilizing MS Project for detailed project scheduling.

Question to collect additional data on larger shifts in the planning and management field where presented. Overall, it appears that the associated tasks are being accomplished using automated information systems (AIS), with increased focus on projects completed by multiple team members by task for increased efficiency as opposed to the traditional assignment of an individual to complete the entire project. Most interviewees expressed a noticed shift in unpredictability of timing and funding of projects, leading to increased difficulty in planning and management. A noted challenge across the data was the ability to hire and on-board quality personnel. Interviewees noted that this challenge seems to be more difficult than in the past.

Insight into who is performing updates to workforce forecasts, how often workforce needs are assessed, and how often workload forecasts are updated was questioned. Five of the nine interviewees stated that upper leadership with input from resource managers or other members of the team perform updates to workforce forecasts. Four of the nine interviewees stated that workforce is assessed on an annual basis and eight of the nine interviewees update workload forecasts on a weekly basis. Although workforce is assessed on an annual basis, the amount of time utilized to review workforce needs varies from interviewee to interviewee, ranging from six to eighteen months, and even as far as three years.

Overall, most interviewees did not view a project being put on-hold or delayed as a major challenge. Eight of the nine interviewees mentioned that if a project is put on hold unexpectedly, they re-assign team members to other work or contact other offices to see if support is needed. The intent of this questioning was to determine how unexpected stoppage of work and re-assignment of staff is handled by each individual and to determine if there were specific processes or tools used to manage this type of event. One of the nine interviewees mentioned that their company uses downtime because of work stoppage or delay to further develop their staff through formal training or opportunities to shadow senior staff. Eight of the nine interviewees detailed collaborative processes to determine project prioritization if deliverables become stacked with decision making conducted by leadership and communicated to the remainder of the team.

All the interviewees identified soft skills (communication, flexibility, levelheadedness, honesty, and sense of your workforce, understanding the big picture) as important skills for workload management in engineering, which is often viewed as a mostly hard skill, technical skill, and knowledge. Five of the nine interviewees confirmed usage of earned value management (EVM) or other tools to measure progress and performance. Within USACE, EVM was only required for mega-projects and the policy requiring its use has since expired. Many interviewees expressed the desire to have a tool that would allow the functionality of EVM – the ability to analyze the cost, budget, and schedule performance of a project – but it is not currently widely used amongst the interviewees. Preferred features to incorporate into the report and dashboard developed through this effort to determine if the team had inadvertently missed an opportunity or could improve upon the product. Six of the nine interviewees mentioned the need to have schedule and budget (planned versus actual) displayed as part of an application. Most of the interviewees are using separate tools for schedule (MS Project), budget (Excel or other), and expressed the challenge with combining the data from the two systems for analysis.

None of the interviewees expressed major changes in their method for forecasting workload since the pandemic began. Three of the nine interviewees stated that there remains a challenge with determining the appropriate balance of in-person versus virtual or remote workers within their organizations. Allowing the interviewees to comment on anything that the researcher did not identify in the previous questions related to workforce planning and workload management yielded three of the nine interviewees detailed difficulties with building the workforce in the current work environment and on-going challenges with the hybrid (in-person and virtual/remote) workplace.

7. Conclusion

There is no single tool widely used that performs both tasks within the same application. Through analysis of the semi-structured interview responses, it is apparent that most leaders within the industry, whether federal or private sector architect-engineering firms, are using a combination of financial applications and Excel with some quantity of manually entered information. Another key theme across the interviewees was that there is does not seem to be a tool that effectively compares budget to schedule but this is a feature that most of the interviewees are seeking or would find valuable in an application. As programs and projects become more fluid, due to funding sources and the passage of massive federal legislation, the need for a tool that allows resource manager and leaders to evaluate multiple courses of action and shuffle resources quickly when things change becomes more critical to evaluate impacts. With the ability to game plan, the ability to produce visually pleasing graphics to assist in “telling to story” to non-technical staff becomes a more valued and sought-after feature. Items like heat maps, line graphs, etc. are useful to the entire team and can be produced easily with the appropriate data and data visualization tool. Although there is no single tool that performs both functions (workforce planning and workload management), there are tools available to assist with mining the data existing in current USACE automated information systems (AIS) and using Power BI or similar data visualization applications is critical as the enterprise moves forward and seeks to modernize its processes.

Overall, COVID-19 does not seem to have had a major impact on how engineering managers and leaders perform workforce planning and workload management. Employees throughout engineering encountered a learning curve when the pandemic started over three years ago, but all have adjusted accordingly and recognized some efficiencies from the mostly hybrid (in-person and virtual) work environment. Although all interviewees agreed that project prioritization is being performed by senior leadership with input from resource managers, clear and frequent communication with staff regarding project prioritization or changes to prioritization is critical to ensure the team remains aware and focused due to the hybrid nature of the work environment. There is not often the opportunity to pull everyone quickly into a conference room to review changes on the go, communications must be deliberate and reach all personnel, whether in-person or virtual. Another recognized theme throughout the research is the challenge in countering the negative impacts of the hybrid work environment, most notably the challenge with fostering camaraderie and sense of ownership and belonging within the workplace. Managers and leaders within organizations need to continue to look for opportunities to build the sense of team while continuing to provide the flexibility so many jobseekers value. Along with decreased camaraderie and sense of ownership and belonging, managers are noticing an increased challenge in hiring and building the workforce. The latest generation of engineering employees value flexibility in work hours and location (telework) and are willing to switch employers more frequently if needed to obtain the valued benefits. Another shift in the industry is the decrease in willingness to work the 40+ hour workweeks that engineering and architecture often require, with more employees requesting to working part time or compressed schedules to maintain a better life work balance. These conclusions are significant shifts in values from those most often performing at the management level in the traditional hierarchy of engineering organizations and pose a challenge for managers and leaders, as the need for more engineers remains constant.

References

[1] 16 Reasons Why Employees Choose To Leave Their Jobs [WWW Document], n.d. . Indeed Career Guide. URL https://www.indeed.com/career-advice/career-development/reasons-employees-leave (accessed 8.27.22).
[2] A multigenerational workforce brings opportunities, challenges for the Corps [WWW Document], n.d. . Southwest. Div. URL https://www.swd.usace.army.mil/Media/News-Releases/Article/503278/a-multigenerational-workforce-brings-opportunities-challenges-for-the-corps/https%3A%2F%2Fwww.swd.usace.army.mil%2FHome%2FArticle%2F503278%2Fa-multigenerational-workforce-brings-opportunities-challenges-for-the-corps%2F (accessed 8.27.22).
[3] Army Civil Works Studies, Projects and Programs to Be Accomplished with Bipartisan Infrast [WWW Document], n.d.. US Army Corps Eng. Hqrs. URL https://www.usace.army.mil/Media/News-Releases/News-Release-Article-View/Article/2903380/army-civil-works-studies-projects-and-programs-to-be-accomplished-with-bipartis/https%3A%2F%2Fwww.usace.army.mil%2FMedia%2FNews-Releases%2FNews-Release-Article-View%2FArticle%2F2903380%2Farmy-civil-works-studies-projects-and-programs-to-be-accomplished-with-bipartis%2F (accessed 8.7.22).
[4] Burnout: 3 Signs To Look For [WWW Document], n.d. URL https://www.webmd.com/mental-health/burnout-symptoms-signs (accessed 8.13.22).
[5] Delisle, J., 2020. Working time in multi-project settings: How project workers manage work overload. Int. J. Proj. Manag., SI: Actors, Practices and Strategy Connections in Multi-Project Management 38, 419–428. https://doi.org/10.1016/j.ijproman.2020.04.001
[6] Gittleman,Maury, n.d. The “Great Resignation” in perspective : Monthly Labor Review: U.S. Bureau of Labor Statistics [WWW Document]. URL https://www.bls.gov/opub/mlr/2022/article/the-great-resignation-in-perspective.htm (accessed 9.3.22).
[7] Great Resignation, 2022. . Wikipedia.
[8] How to Attract and Retain a Talented Workforce [WWW Document], 2018. . Natl. Leag. Cities. URL https://www.nlc.org/article/2018/08/03/how-to-attract-and-retain-a-talented-workforce/ (accessed 8.27.22).
[9] Jamshed, S., 2014. Qualitative research method-interviewing and observation. J. Basic Clin. Pharm. 5, 87–88. https://doi.org/10.4103/0976-0105.141942
[10] Kairinos, N., 2022. How to Prevent the Great Resignation. ITNOW 64, 12–13. https://doi.org/10.1093/itnow/bwac039
[11] Kang, O.S., Hanna, n.d. Young federal government employees are leaving their jobs at higher rates than their older counterparts: report [WWW Document]. Bus. Insid. URL https://www.businessinsider.com/young-government-workers-leaving-jobs-higher-rates-than-older-counterparts-report-2022-7 (accessed 8.28.22).
[12] Keup, M., 2022. What Is Microsoft Project? Uses, Features and Pricing [WWW Document]. ProjectManager. URL https://www.projectmanager.com/blog/what-is-microsoft-project (accessed 8.30.22).
[13] Missions -- Headquarters U.S. Army Corps of Engineers [WWW Document], n.d. URL https://www.usace.army.mil/Missions.aspx (accessed 8.27.22).
[14] OPM’s Workforce Planning Model, n.d. 3.
[15] Project management goal: Create a new project schedule in Project desktop [WWW Document], n.d. URL https://support.microsoft.com/en-us/office/project-management-goal-create-a-new-project-schedule-in-project-desktop-91e314ed-af31-4043-be6f-61a7ea0d89ba (accessed 9.3.22).
[16] Resource leveling, 2022. . Wikipedia.
[17] United States Army Corps of Engineers, 2022. Wikipedia.
[18] Visual project management [WWW Document], n.d. URL https://www.pmi.org/learning/library/visual-project-management-visual-elements-9862 (accessed 9.4.22).
[19] Westland, J., 2022. Workload Management: How to Manage Your Team’s Workload [WWW Document]. ProjectManager. URL https://www.projectmanager.com/blog/how-to-manage-your-teams-workload (accessed 8.7.22).

EVALUATION OF MODULAR CONSTRUCTION METHODS VERSUS TRADITIONAL CONSTRUCTION METHODS FOR ARMY CONSTRUCTION PROJECTS

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Abstract

This research study focuses on examining the Army's facility construction program during the fiscal years 2006 through 2013, known as Military Construction Transformation. For this program, the Army had goals to build better facilities, constructed faster and at less cost. To accomplish this, the Army gave contractors additional consideration for contract awards if the contractors proposed innovative design solutions, such as modular construction. This research examines construction costs, construction schedules, and maintenance records to determine if the Army's goals were met. There were more than 7,000 maintenance records available, covering more than ten years for the facilities evaluated. The results of the data revealed that modular construction is not providing the durability and maintainability that the Army paid for when compared to conventional construction through comparative case studies. A recommendation was provided as well as considerations for future research.

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Keywords: construction, cost, facility, modular, traditional

1. Introduction

Billions of dollars are spent on Army facilities for both new construction and maintenance. In 2006 the United States Army, through the United States Army Corps of Engineers (USACE), implemented a construction buildout of $44.6 Billion that was required to be completed within the Fiscal Year (FY) 2006 to FY 2013 timeframe. To accomplish the construction on a highly accelerated schedule and massive scale, the Army relaxed several requirements that included allowing Type V Construction, such as modular buildings, and allowing industry criteria to be used instead of all Unified Facility Criteria (UFC) requirements that are highly prescriptive. This initiative also emphasized using Design-Build (D-B) instead of Design-Bid-Build (D-B-B) procurements. The Army called this endeavor MILCON Transformation, abbreviated as MT. MILCON stands for Military Construction.

By adopting performance-based criteria and industry best practices, contractors could utilize Type V (combustible) construction, which was previously not permitted in Military Construction. Type V construction enables the use of "modular units" – pre-manufactured sections constructed in workshops and delivered and installed onsite. Type V construction is built from combustible light wood framing-the least fire-resistant of all construction types. Fire ratings fall to zero for Type V-B construction (Allen & Lano, 2013). Realizing the need for fast construction, the Army placed incentives in D-B Requests for Proposals (RFP), stating contractors that proposed innovative design solutions, such as modular construction, would receive additional consideration from the source selection evaluation board. The Army was aware that the modular facilities would not provide the same longevity when compared to a concrete structure. The MILCON Transformation program specifically sought a 25-year rehabilitation/repurpose cycle instead of the 50-year cycle typical of previous construction requirements. Through onsite post-occupancy evaluations of the constructed facilities, many installation facility managers stated concerns that the buildings constructed using modular methods are inferior and perform poorly compared to buildings constructed using more robust and restrictive methods.

2. Research Background

In 2006, the United States Army Corps of Engineers (USACE) was responsible for executing six major Army initiatives that required the complete construction of facilities totaling approximately $44.6 Billion (FY 06 – FY 13) in a short timeframe. This requirement necessitated changing the current design, construction, and acquisition processes. Corps of Engineers leadership issued orders to update design and construction processes, titled, *USACE Policy on Applicability and Use of the Military Construction Transformation Model Request for Proposal*. This order stated: The Army faces a significant resource shortfall in providing permanent facilities to support a transforming Army at war. The Vice Chief of Staff of the Army (VCSA) has directed that standard facilities will be constructed to meet Warfighter functional and operational capabilities. This includes providing facilities that meet the quality-of-life features based on non-military considerations, such as equivalent living conditions in academia, and working facilities that meet requirements for current and future use, such as tactical equipment maintenance facilities that can service existing vehicles and vehicles the Army intends to field in the next five to ten years.

The Department of Defense budget request for the construction of new facilities and sustainment, restoration, and modernization is $21 Billion for FY 21. Even with this funding, it, on average, funds 80 percent of DOD facility sustainment requirements across the enterprise [5]. A backlog of $134 Billion in Renovation and Modernization (R&M) projects and low overall funding levels continue to cause the degradation of Army infrastructure [4]. Existing research has analyzed how the DOD and Army best utilize their construction funding. There is well-researched information focusing on decision-making when various construction methods can be used, as well as the cost and schedule impacts of different construction methods. For example, Modularization has the potential to address many recurring industry challenges, including a shortage of skilled workforce, tight budgets, schedule compression, and reduced site risk by reducing onsite labor [2]. Average construction costs per square foot are lower for facilities constructed with combustible materials than for facilities with higher levels of fire protection [7]. The Army appears to have achieved some savings in selected construction projects by expanding the use of wood materials and modular construction methods for some of its facilities. Still, the Government Accountability Office found little quantitative data on whether the use of these materials and methods will result in savings over the long term compared to the traditional use of steel, concrete, and masonry materials and onsite building methods [9]. Research on the overall Department of Defense facility spending between 2010-2016 shows $4.2 Billion in savings [1].

3. Research Aim

The scope of the research will look at unaccompanied personnel housing and administrative facilities constructed at Fort Bliss, TX, and Fort Carson, CO, as these facilities were constructed for the same purpose using both conventional and modular construction. This will allow for the most relevant analysis possible. The research will include maintenance records for the buildings from the first available record to 2022. Those buildings erected before MT are considered “legacy” facilities and were subjected to all applicable UFCs, establishing stringent construction requirements. These facilities required Type II construction [3]. Type II requires that building elements be of noncombustible materials [6]. As such, legacy facilities were not considered for evaluation.

The objective of this study is to explore whether the Army’s modular buildings are inferior in quality and do not provide efficient lifecycle facilities. The study focused on Unaccompanied Enlisted Personnel Housing (UEPH), also known as barracks and Administrative Facilities.

Archival data will provide information on the following themes:

1. Did modular construction hold up over time compared to conventional construction?
2. Are building systems in modular facilities performing as well as systems in conventional construction?
3. Did the Army get what it paid for in modular construction regarding durability and maintainability?

4. Literature Review

Modular construction in the context of this research is the method of assembling as much of a facility as possible, including structure, building systems, and finishes in a factory setting, as well as transporting the modular unit to a construction site for final assembly and completion. MT demonstrated that facilities could be constructed quickly and cheaper than before MT [1]. The compromise was the overall useful life of the facility before a major renovation, which was reduced to 25 years from 50 years. Before MT, the average construction duration of a $25 Million barracks was approximately two years or 720 calendar days. MT required that the total number of proposed calendar days for design and construction through completion, ready for turnover, shall not exceed 540 calendar days [11]. Since the projects were first initiated, many Army Installation Departments of Public Works (DPW) were concerned that the facilities would be poorly constructed and cause a significant resource drain on limited maintenance funds. The U.S. Army Corps of Engineers Inspector General developed a report that stated: Installation officials feared that the less-stringent commercial specifications and construction standards allowable under MT would result in increased Operations and Maintenance (O&M) costs in the future – additional expenses that already stressed DPW budgets might not be able to afford.

Senior Army leadership was committed to providing equitable delivery of projects within the Army's Total Obligation Authority to meet both mission and quality of life requirements. (Temple, 2006). USACE leadership further stated that in order to meet these challenges, the Army is implementing MT. A key component to successfully implementing MT was the Model RFP. The Model RFP, also known as the RFP Wizard, provided a web-based tool to develop D-B RFPs for standard Army facility types quickly. The technical performance requirements suitable for a D-B RFP, such as the architecture, mechanical, electrical, and structural elements, were developed in advance of projects for standard facility types. Minimal input was required from the technical team developing the D-B RFP; only the site, infrastructure and aesthetics of the building exterior required significant technical resources.

Many with a professional background indicated during post-occupancy reviews that the potential increased cost in the future to maintain facilities constructed using commercial construction standards outweighed any perceived cost savings claimed during the project delivery process. Almost all admitted that it was too early to conclude; however, no data was available to support their contentions at this point [10]. This research will look at the data collected and see if there is data-driven validity to the concern that Type V and modular construction are an inferior product. Given the significant dollars in the program, providing Type V facilities that meet service life and quality standards can save taxpayer money versus going back to more restrictive construction.

Modular buildings are manufactured facilities that provide factory-controlled environments in an assembly line configuration. Completing as many of the building components in a controlled environment allows the manufacturer to minimize inclement weather impacts, manage supply lines of individual components, and control quality through the assembly line method. Recent academic research in the last ten years, as well as older research, has referenced the following for a consistent definition of the term module, “A module is a product resulting from a series of remote assembly operations. It is usually the largest transportable unit or component of a facility. A module consists of a volume fitted with all structural elements, finishes, and process components, which regardless of system, function, or installing craft, are designed to occupy that space. Modules may contain prefabricated components or preassemblies and are frequently constructed away from the job site” [8].

It is noted that the Types of Construction (Type II and Type V) discussed in this research are fire-resistance ratings for exterior walls based on fire separation distance [6]. This fire resistance rating was frequently used to convey the quality of materials and is at the heart of the research. The use of “Type II” and “Type V” is used synonymously with quality in the Army vernacular. This is partly because, in Type II buildings, the materials and components are required to be non-combustible. As such, all the components that go into building assemblies must be rated as non-combustible. Electrical wiring in a Type II facility must be run in conduit, whereas a Type V facility may use non-metallic cable such as Romex. Light fixtures and outlet boxes may also be rated. Also, HVAC penetrations can be more sophisticated in Type II Construction, and finishes may have a higher rating. Substantial research has been conducted on modular construction, including the categories of modular construction and research on exactly how much academic literature has been developed on the modular construction industry.

Much of the existing literature discusses the use of modular construction in the industry and how it benefits project completion. One academic journal provided a succinct description of why modular is not used. *An Investigation of Critical Factors and Constraints for Selecting Modular Construction Over Conventional Stick-Built Technique*. This journal discusses that more coordination in the planning and procurement process is required, and there is less flexibility to make changes late in the project. The journal provides an excellent evaluation of why modular is not used in two different sections. The first states, “In most cases, the decisions are made based on the experience and gut-feelings of senior project managers and modularization experts” [2]. This is followed up with the following conclusion, “Some of the barriers preventing the widespread use of modularization for commercial building projects include lack of modularization provisions in typical project design, lack of awareness of the benefits of modular construction among owners, the non-availability of prefabrication units in the project vicinity, restricted site layout, and modular design rigidity” [2].

Few academic journals or articles go into detail, specifically discussing the Army’s use of modular construction during the 2006-2013 timeframe and comparing the results to traditional construction. The most relevant data is a Government Accountability Office (GAO) report to the House of Representatives Armed Services Committee. This report published in 2010 and did not have the opportunity to evaluate the buildings in a long-term manner to assess their lifecycle performance. Acknowledging this, the GAO report stated, “Without long-term or life-cycle analyses that consider not only initial construction costs but also possible differences in facility service lives and annual operating and maintenance costs between the construction alternatives, it is not clear that the Army’s expanded use of wood materials and modular building methods will achieve the Army’s intended purpose of reduced facility costs over the long term” [9].

Army Corps of Engineers personnel visited several different modular manufacturers during the initial stages of the MT buildout. The modular manufacturers indicated through in-person interviews at the time that the Army’s requirements for the facilities were more robust than the traditional manufacturing of commercial facilities and residential buildings. The increased robustness was based on Anti-Terrorism and Force Protection (ATFP) requirements and the prevention of progressive collapse requirements when the constructed facility would be three stories or higher. These requirements required the manufacturers to increase overall structure rigidity and add considerations for glazing for blast resistance, as well as other building system considerations not present in commercial or residential construction. The modular manufacturers would have to set up the assembly lines specific to the Army’s projects. They would run the entire order through the plant at once, so the assembly line could be converted back to standard lines of business.

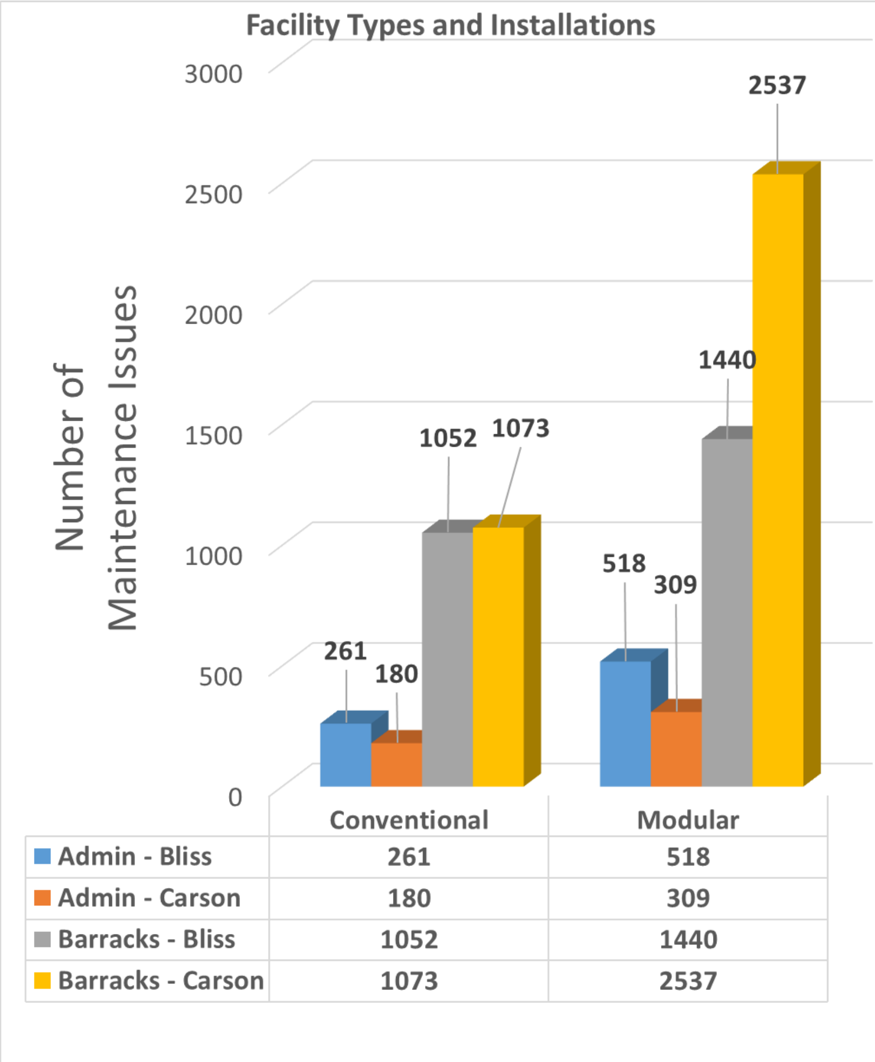
5. Research Methodology

Research was conducted using a quantitative method of analyzing archival data from initial construction award documentation and maintenance records for a specially selected number of facilities. Eight facilities across two locations will be utilized for the research, because the facilities provide the opportunity to examine similar buildings constructed at the same time. Four buildings used modular construction and four buildings used traditional methods.

Four buildings are located at Ft. Bliss, TX and include two barracks (one modular and one traditional construction) and two administrative facilities (one modular and one traditional construction). The second set of four buildings are located at Ft. Carson, CO and include the same make up and construction types as Ft. Bliss. Between the eight buildings, there are more than 7,300 maintenance call records to analyze spanning more than ten years.

6. Results and Discussion

Out of the 7,370 maintenance calls, there were more calls for modular facilities than those constructed via conventional methods. The four modular facilities received a total of 4,804 maintenance calls compared to the 2,566 that were recorded for the four conventional facilities which is depicted in Table 10 below.



	Conventional	Modular
Admin - Bliss	261	518
Admin - Carson	180	309
Barracks - Bliss	1052	1440
Barracks - Carson	1073	2537

Table 10 Maintenance Calls

An interesting result of the data analysis is that all the facilities receive a similar percentage of building system issues and normal maintenance. The average percentage across all facilities for building system issues is 61%. The average percentage across all facilities for normal maintenance issues is 36%. The most noticeable difference is the total number of service calls received for the facility types. The modular facilities received many more maintenance calls. For the Barracks, maintenance calls to modular facilities represents 65% percent of the total. Conventional facility maintenance calls are only 35% of the total. For the Admin Facilities, maintenance calls to modular facilities represents 65% percent of the total. Conventional facility maintenance calls are only 35% of the total.

All modular facilities analyzed had more maintenance calls than the comparable facility using conventional construction. This is a strong indicator that the modular facilities are not holding up over time compared to conventional construction and that the building systems in modular facilities are not performing as well as the conventionally constructed counterpart. “The Army set goals to reduce its estimated construction costs by 15 percent and building timelines by 30 percent” [9]. Based on the projects analyzed, the average cost savings were 13%, but on average, it took 16% longer to construct the facilities. It is interesting to note, that modular construction took longer to complete for both installations, the modular barracks at Ft. Bliss and the Admin Facility at Ft. Carson.

A significant limitation is the small sample size of Army facilities constructed at the same time that include both modular and conventional construction. The selection of facilities was made to evaluate the differences most accurately in first costs, construction duration and total maintenance calls. However, the number of maintenance calls, more than 7000, provides a large sample size to evaluate across the facility types selected. Additionally, there was bias in the fact that the author was involved with the MILCON Transformation program attempting to achieve all the goals stated. Results of the data were not favourable to continuing modular construction.

6. Conclusion

The goal of MILCON Transformation was to provide facilities that could be built better, faster, and cheaper. The modular facilities analysed experienced 87% more maintenance calls than the conventionally constructed counterparts. This is almost twice as many service calls to maintain the facility. An interesting data point is that the type of calls are similar between routine maintenance and a building system issue for both types of construction; however, there are almost twice as many maintenance requests to the modular facilities. The Army's goal was to reduce construction timelines by 30% when compared to conventional construction methods. The data analyzed indicates it took on average 16% more days to complete the construction of modular facilities when compared to the conventionally constructed counterpart. Another goal was to reduce cost by 15%. The data indicates the costs savings was less than 15%.

Modular facilities require almost twice as many maintenance calls to reach the 25-year rehabilitation/repurpose cycle, it does not appear modular construction is holding up over time compared to conventional construction and that modular facilities are not performing as well as conventional construction regarding durability and maintainability. In addition, the cost savings indicate the Army's goals were not achieved. Based on the fact that none of the MILCON Transformation goals appear to be met, modular cannot be recommended in future Army construction projects. Based on the data available, catastrophic failure of building systems is rare. With the limited data available, the Army would need to do determine if fiscal programming requirements need to be allocated based on housing soldiers on the normal occurrence of service calls, or what happens when a catastrophic failure occurs. Future research can evaluate the potential impact of catastrophic conditions.

References

[1] Angell, C. E. E., White, Dr. E. D., Ritschel, Dr. J. D., & Thal, Dr. A. E. (2020). Analysis of Military Construction Cost Growth in USAF Major Defense Acquisition Programs. *Defense Acquisition Research Journal*, *27*(92), 168–193. https://doi.org/10.22594/dau.19-840.27.02

[2] Azhar, S., Lukkad, M. Y., & Ahmad, I. (2013). An Investigation of Critical Factors and Constraints for Selecting Modular Construction over Conventional Stick-Built Technique. *International Journal of Construction Education and Research*, *9*(3), 203–225. https://doi.org/10.1080/15578771.2012.723115

[3] Military Handbook—Fire Protection for Facility Engineering, Design, and Construction, MIL-HDBK-1008C 19 (1994). https://safety.army.mil/Portals/0/Documents/ON-DUTY/WORKPLACE/FIREPROTECTIONLIFESAFETYCODE/Standard/1008c.pdf

[4] Dias, S. (2020). *FY21 MILCON*. SAME 2020 FY21 MILCON.

[5] *DOD Releases Fiscal Year 2021 Budget Proposal*. (n.d.). U.S. DEPARTMENT OF DEFENSE. Retrieved June 26, 2021, from https://www.defense.gov/Newsroom/Releases/Release/Article/2079489/dod-releases-fiscal-year-2021-budget-proposal/

[6] International Building Code,Chapter 6 Types of Construction § 602 (2017).
https://codes.iccsafe.org/content/IBC2018/chapter-6-types-of-construction

[7] Samaras, C., Haddad, A., Grammich, C. A., & Webb, K. W. (2013). The Role of Building Codes in Determining Construction Material. In *Obtaining Life-Cycle Cost-Effective Facilities in the Department of Defense* (pp. 27–32). RAND Corporation. https://www.jstor.org/stable/10.7249/j.ctt3fh1bc.11

[8] Tatum, C. B., Venegas, J.A., & Williams, J. M. (1987). Constructability improvement using prefabrication, pre-assembly and modularization. *Austin: Construction Industry Institute.*, *Technical Report 297*.

[9] U. S. Government Accountability Office. (2010, April). *Defense Infrastructure: DOD Needs to Determine and Use the Most Economical Building Materials and Methods When Acquiring New Permanent Facilities*. https://www.gao.gov/products/gao-10-436

[10] Inspection of MILCON Transformation, (2010).

[11] MILCON Business Process—Model RFP Implementation Guide, § 2.0 Contract Line Item Schedule (2006). https://rfpwizard.mrsi.erdc.dren.mil/MRSI/content/Model%20RFP/MILCON/MBP%20Implementation%20Guide/rfpimplementationguidelines.pdf.

EVOLUTIONARY ALGORITHMS FOR CONSTRUCTION SITE LAYOUT PLANNING

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Abstract

The arrangement of temporary facilities within a construction site is essential for successfully undertaking a project, as it enhances productivity and ensures both safety and environmental protection. The Construction Site Layout Planning (CSLP) problem is a challenging discrete combinatorial optimization problem involving multiple objectives and has been tackled using various methods, from linear programming to heuristic and meta-heuristic techniques. Evolutionary algorithms have patently been preferred for solving the CSLP problem due to their ability to provide efficient (near-optimal) solutions in reasonable computational time. The present work aims to comparatively evaluate the effectiveness of five well-known evolutionary algorithms in terms of these performance indicators based on a number of case studies of different structure and characteristics. The model implementation is structured in an Excel environment to facilitate the problem setting and calculations while the optimization algorithms have been implemented in the Matlab software. The examined case studies include simple, single-objective formulations (i.e., minimizing the total traveling distances among facilities) and multi-objective formulations that consider, in addition, preferences or constrains in facility setting to account for operational, safety, and environmental considerations. The evaluation results indicate that all methods perform reasonably well from a practical point of view, however, those based on harmony search, simulated annealing, and particle swarm optimization appear to be more flexible in attaining better solution quality and lower computational time.

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Keywords: construction operations, construction site layout planning, evolutionary algorithms, metaheuristics, optimization.

1. Introduction

Cost, safety, and environmental protection are critical factor for designing an efficient construction site. The Construction Site Layout Planning (CSLP) problem deals with determining the optimum placement of the temporary facilities within the construction site area to facilitate the operational plan of the construction work. The main objective of the CSLP analysis is to minimize the resource consumption by reducing the cost associated with the resource movements among facilities (traveling distance reduction) while satisfying any spatial or other constraint of the problem.

The CSLP problem is developed in two types, according to the way that the temporary facilities are allocated within the available space of the construction site. The general formulation in which the facilities can be freely assigned in any unoccupied area is known as the "facility-to-site (FSP)" problem. This approach efficiently exploits the whole construction site area; however, as the number of facilities or spatial constraints (restricted areas) increase, the problem becomes more complex and requires increased computational effort. A simplified consideration to overcome this difficulty is to pre-determine several specific areas for potential facility allocation and searching for the best combination of facility placement within these areas, leading to the "facility-to-location (FLP)" problem. The problem can be further distinguished to an "equal" or "un-equal" area problem depending on whether all facilities can fit to all locations or not.

The CSLP "facility-to-location" problem falls within the NP-hard combinatorial optimization problems. As the exhaustive search is not tractable, meta-heuristic techniques prevail in solving the problem, as they can promptly provide efficient (near-optimal) solutions. Most existing research efforts employ a specific type of algorithm and focus on describing the mathematical formulation and evaluating its performance based on some case studies and operational scenarios. In the present study, a number of known evolutionary algorithms are implemented and comparatively evaluated to explore the pros and cons of such methods in optimizing the CSLP problem.

2. Background

The literature review indicates that several studies have aimed at solving the facility-to-location CSLP problem by proposing various models and techniques, from Linear programming (LP) to swarm intelligence (SI) and evolutionary algorithms (EA). Yeh [1] combined Artificial Neural Networks (ANN) with Simulated Annealing (SA), while Tam et al. [2] introduced a non-structural fuzzy decision support system that integrates both expert judgment and computer decision modeling.

Genetic algorithms (GA) are the most widely applied evolutionary algorithms. Li and Love [3,4] introduced models for equal and unequal "facility to location" CSLP problems utilizing GA for optimization, while Mawdesley [5] proposed a sequence-based genetic formulation applying various values of crossover and mutation operators. Cheung et al. [6] handled a site precast yard layout problem through Palisade Evolver software, and Lam et al. [7] introduced GAs conjoined with a max-min ant system for improving the quality of the initialization. Finally, Papadaki and Chassiakos [8] presented a model involving multiple parameters and employed GAs for the implementation.

Swarm Intelligence (SI) algorithms have also been implemented to solve the CSLP problem. Gharaie et al. [9] illustrated an Ant Colony Optimization (ACO) methodology, while Lam et al. [10] merged fuzzy logic and entropy technique with an Ant Colony Optimization (ACO) algorithm. Calis et al. [11] demonstrated an Ant Colony Optimization algorithm with Local Analysis (ACO-LA) to improve the quality of the results, while later [12], they expanded this research by introducing parametric analysis.

Liang et al. [13] employed the strategies of Tabu Search to solve the models of Li and Love [4], while Gholizadeh et al. [14] developed a Harmony Search (HS) algorithm evaluating its performance in the same benchmark model. Zhang and Wang [15] presented a particle swarm (PSO-based) optimization approach for solving unequal-area CSLP problems. Furthermore, Lien et al. [16] introduced a Particle Bee Algorithm (PBA), which combines the benefits of Particle Swarm and Artificial Honeybees in global and local analysis respectively.

The literature review indicates that most of the research efforts focus on developing innovative algorithms adapted to specific CSLP problem requirements and utilizing previous research as a benchmark for the implementation. Therefore, the strengths and limitations of each algorithm may not be readily apparent. The present study intends to provide a comparative evaluation among several existing algorithms in terms of solution quality and computational efficiency. A number of operational scenarios are analyzed to broadly support the algorithm evaluation.

3. Model formulation

For the purposes of the current research, the "facility-to-location" model presented in Farmakis and Chassiakos [17] has been considered for the comparative evaluation of the algorithm performance. This model involves multiple objectives, parameters and constraints in the directions of construction efficiency, safety, and environmental protection. The model includes parameters related to direct expenditures for facility placement and transport operations associated with resource flows, distances, and operational conditions. Besides direct costs, additional parameters are considered to ensure that construction processes run smoothly, efficiently, and safely. These parameters are modelled as proximity (or remoteness) preferences (or constraints) between pairs of facilities or between facilities and locations. The optimization model is structured upon the Quadratic Assignment Problem (QAP) and is mathematically formulated as follows:

$$MinF = w_1 f_1 + w_2 f_2 \quad (1)$$

where:

$$f_1 = TC = \sum_{i=1}^{n}\sum_{x=1}^{n}\sum_{j=1}^{n} \delta_{xi} f_{ij} u_{ij} d_{ij} + \sum_{i=1}^{n}\sum_{x=1}^{n} \delta_{xi} c_{xi} \quad (2)$$

$$f_2 = SP = \sum_{i=1}^{n}\sum_{x=1}^{n}\sum_{j=1}^{n} \delta_{xi} a_{ij} e_{ij} + \sum_{x=1}^{n}\sum_{i=1}^{n} \delta_{xi} a_{xi} f_{xi} \quad (3)$$

subject to:

$$\sum_{x=1}^{n} \delta_{xi} = 1, \qquad x = 1,2,\ldots,n \qquad and \qquad \delta_{xi} = 0-1 \quad (4)$$

$$\sum_{i=1}^{n} \delta_{xi} = 1, \qquad i = 1,2,\ldots,n \qquad and \qquad \delta_{xi} = 0-1 \quad (5)$$

where f_1 is the function of the total cost, f_2 is the equivalent safety and preference component (representing bonuses or penalties for preferences and constraints), w_1 and w_2 are weight coefficients, n is the number of facilities and locations, δ_{xi} is a binary permutation parameter connecting facility i to location x, f_{ij} is the frequency of trips between facilities i and j, u_{ij} is the unit transport cost of the movements between i and j, d_{ij} is the Euclidean distance between i και j, c_{xi} is the construction cost for facility i at location x, α_{ij} and α_{xi} are binary variables indicating whether two facilities i and j or facility i and location x are in an acceptable distance range, e_{ij} and f_{xi} are bonuses (or penalties) if the corresponding distance preferences or constraints are (not) satisfied.

4. Algorithms and software

A preliminary evaluation of several commonly utilized algorithms showed that algorithms adapted to solve pure permutation formulations modeled as a Quadratic Assignment Problem (QAP) can provide efficient (near-optimal) solutions to the "facility-to-location" problem in reasonable computational time. As a result, the current research focuses on five robust permutation-based algorithms, namely Genetic Algorithm (GA), Particle Swarm Optimization Algorithms (PSO), Simulated Annealing Algorithms (SA), Harmony Search Algorithms (HS), and Differential Evolution Algorithms (DE).

Two commercial software tools have been utilized in the current study for model implementation, Microsoft Excel for data handling and performing the necessary calculations and Matlab for developing the algorithms. Every Microsoft Excel spreadsheet consists of the data entry fields (e.g., frequencies of trips between facilities, location coordinates, etc) and the output presentation while the calculations associated with the optimization algorithms are implemented in the Matlab software.

5. Case studies

Three operational scenarios with increasing level of complexity are employed to evaluate the algorithm performance. C1 refers to a small-sized (11 facilities and 11 locations) problem with a single objective of minimizing the transportation cost of resource movements ([8], [9]). C2a and C2b are mostly directed to the mutli-objective formulation in which the input data of Tables 1 to 3 and Figure 1 apply (16 facilities are to be allocated in 20 available sites). In C2a, the main and side gates need be placed close to the access roads with a properly scaled bonus (-3000), if succeeding so. In C2b, the following preferences and constrains are further considered: a) the concrete batch plant needs to be placed close to the reinforcement steel workshop and the cement/aggregate storage yard to enhance productivity, b) the site office should be located close to the side gate to ensure safe personnel entrance, and c) the fire equipment storage should be placed adjacent to the electric generator & fuel storage for safety reasons. Appropriate bonuses (-50) are imposed for each preference accomplishment. Unit costs of 0.002, 0.004 and 0.006 per m are applied for human resource, light vehicle, and heavy truck movement respectively.

Table 1. Facilities and construction costs

	FACILITY	Constr. Cost
1	Building	0
2	Main gate	15.000
3	Side gate	10.000
4	Site office	25.000
5	Labor rest area	25.000
6	Guard house	10.000
7	Concrete batch plant	40.000
8	Reinforcement steel workshop	30.000
9	Scaffold storage yard	25.000
10	Equipment maintenance shop	30.000
11	Warehouse (Material storage yard)	25.000
12	Cement/aggregate storage yard	30.000
13	Electric generator	10.000
14	Fuel storage	25.000
15	Fire equipment storage	15.000
16	Electricity equipment & water-supply	10.000

Table 2. Resource movement frequencies between facilities

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	0	9	2	6	4	1	9	9	9	9	6	2	1	3	2	2
2	9	0	2	4	2	1	6	6	3	6	9	9	2	6	2	2
3	2	2	0	6	4	2	2	2	2	2	2	2	1	2	2	1
4	6	4	6	0	2	1	4	6	4	4	4	4	1	1	1	1
5	4	2	4	2	0	1	2	2	2	2	2	2	1	1	1	1
6	1	1	2	1	1	0	1	1	1	1	1	1	1	1	1	1
7	9	6	2	4	2	1	0	2	1	6	4	9	1	6	2	1
8	9	6	2	6	2	1	2	0	6	6	4	2	1	4	2	2
9	9	3	2	4	2	1	1	6	0	4	2	2	1	4	1	1
10	9	6	2	4	2	1	6	6	4	0	9	3	2	6	2	1
11	6	9	2	4	2	1	4	4	2	9	0	2	1	3	2	1
12	2	9	2	4	2	1	9	2	2	3	2	0	1	6	1	1
13	1	2	1	1	1	1	1	1	1	2	1	1	0	1	2	1
14	3	6	2	1	1	1	6	4	4	6	3	6	1	0	2	1
15	2	2	2	1	1	1	2	2	1	2	2	1	2	2	0	1
16	2	2	1	1	1	1	1	2	1	1	1	1	1	1	1	0

Table 3: Location coordinates

Location	X	Y
1	20	10
2	20	45
3	10	70
4	30	90
5	20	110
6	30	135
7	50	140
8	70	125
9	90	140
10	120	120
11	140	135
12	140	100
13	130	70
14	140	45
15	130	30
16	110	20
17	90	40
18	70	20
19	40	30
BUILDING	80	80

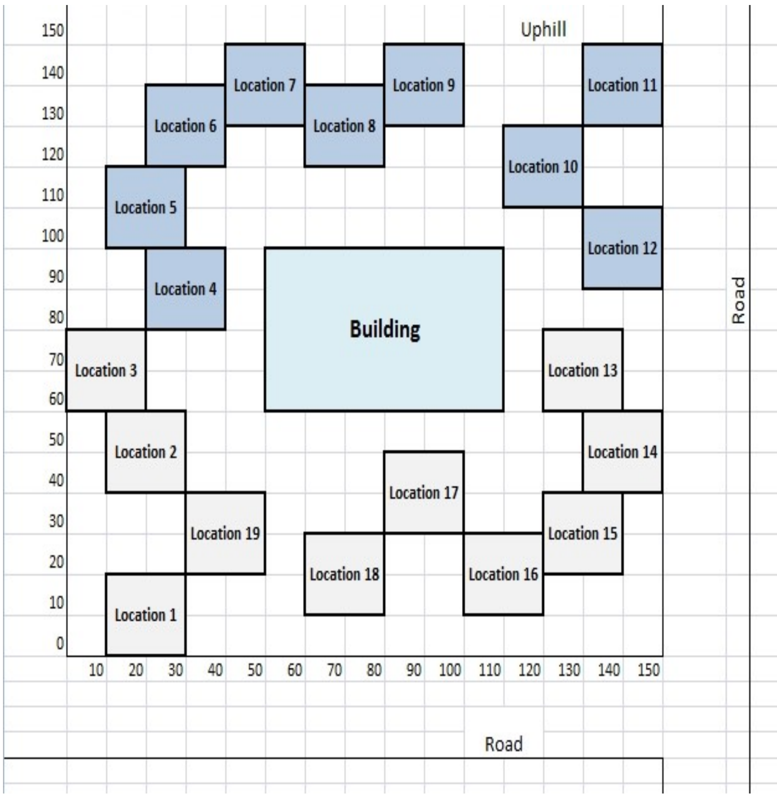

Figure 1. Construction site layout

6. Results

Multiple runs of each algorithm have been performed to account for the stochastic search process and the results of all cases are presented in Table 4. In case C1 (small-size problem), all algorithms provide comparable performance. Among them, HS and PSO can be considered the most robust algorithms with good convergence performance. In case C2a, while SA develops the best value in a single run, HS appears to generally be the most efficient algorithm, providing near-optimal solutions in all iterations. In terms of time requirement, these two algorithms generate effective layouts in approximately half time compared to all other algorithms. Finally, in case C2b, the results show that SA, PSO, HS, and GA present comparable performance in terms of the optimal value acquisition, with PSO reaching the best value among all runs. Further, HS and SA require the least time. A graphical representation of the collective results, in terms of deviations from the best value in each case, is shown in Figure 2. The graph indicates that HS and SA appear to perform better than other algorithms; however, the outcome needs further validation with larger and more complex case studies

Table 4: Algorithm performance evaluation results

Case Study	Evaluation parameter	HS	PSO	SA	DE	GA
C1	Best value	**12,150**	**12,150**	**12,150**	12,266	12,306
	Average value	**12,259**	12,294	12,405	12,370	12,449
	Standard deviation (SD)	67.4	139.2	204,5	**58,5**	118.5
	Running time (min: sec)	7:40	10:30	**7:10**	8:40	11:30
C2a	Best value	40,657	40,913	**40,500**	41,700	41,581
	Average value	**40,927**	41,521	41,528	42,737	42,515
	Standard Deviation (SD)	**260**	776.0	545.8	603	591
	Running time (min:sec)	19:50	34:10	**19:03**	32:21	33:21
C2b	Best value	494	**477**	485	532.4	486
	Average value	503.2	495.2	**494.8**	535.74	508.8
	Standard Deviation (SD)	10.5	10.1	5.5	**2.2**	18.0
	Running time (min:sec)	20:30	28:30	**19:20**	33:25	32:12

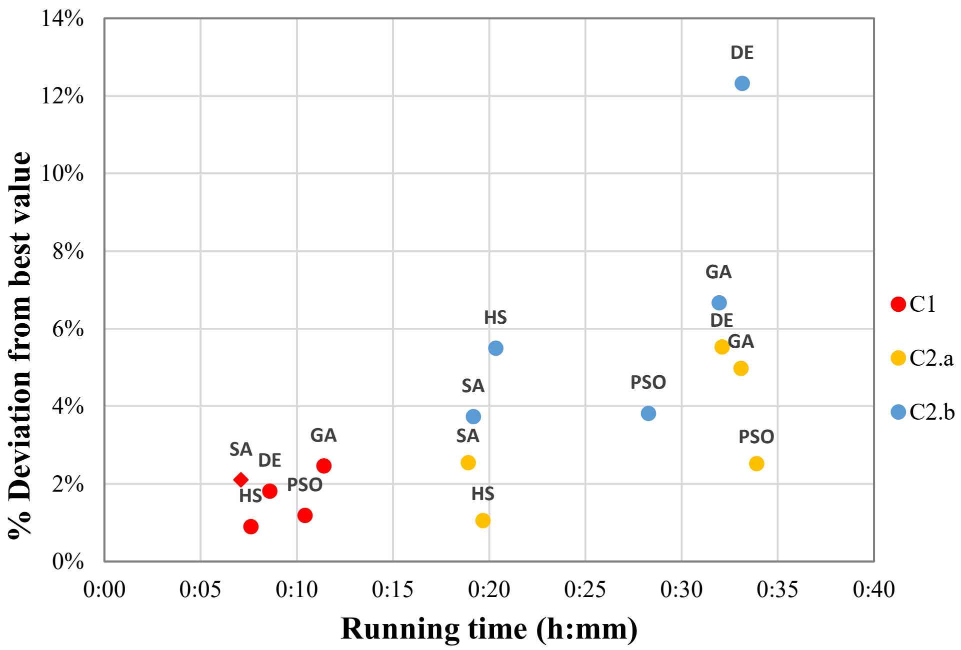

Figure 2. Comparative algorithm performance results in the three cases studies

7. Conclusions

Two case studies and three operational scenarios have been employed to comparatively evaluate the performance of five metaheuristic algorithms in solving the "facility-to-location" CSLP problem. All algorithms can provide acceptable (near-optimal) solutions within reasonable computational time with both performance indexes to degrade as the size and complexity of the problem increase. The results of this initial investigation indicate that SA and HS may be the most promising algorithms for the specific problem. In particular, SA is a non-population-based method, utilizing temporary memory instead, and usually leads to fast and acceptable convergence. HS emerges as a stable algorithmic approach due to the improvisation process which adds new data in the solution population. PSO is a reliable algorithm, especially in larger and more complex cases, and tackles all cases quite efficiently as particles are influenced by the best-found running solution; however, it requires increased running time due to the required internal computations. DE presents comparable performance with other methods in small-sized problems but this performance appears to decay in larger-scale problems because candidate changes between iterations are imperceptible. Similarly, GA performance deteriorates with the problem size and this may be the result of the population-based algorithm structure and the limited influence of the running best solution into the new gene development. The above outcomes can be considered indicative and further analysis is required to obtain a more robust evaluation.

References

[1] I.-C. Yeh, “Construction-Site Layout Using Annealed Neural Network,” *Journal of Computing in Civil Engineering*, vol. 9, no. 3, pp. 201–208, Jul. 1995, doi: 10.1061/(asce)0887-3801(1995)9:3(201).

[2] C. S. Tam, T. K. L. Tong, A. W. T. Leung, and G. W. C. Chiu, “Site Layout Planning using Nonstructural Fuzzy Decision Support System,” *Journal of the Construction Division and Management*, vol. 128, no. 3, pp. 220–231, Jun. 2002, doi: 10.1061/(asce)0733-9364(2002)128:3(220).

[3] H. Li and P. E. D. Love, “Site-Level Facilities Layout Using Genetic Algorithms,” *Journal of Computing in Civil Engineering*, vol. 12, no. 4, pp. 227–231, Oct. 1998, doi: 10.1061/(asce)0887-3801(1998)12:4(227).

[4] H. Li and P. E. D. Love, “Genetic search for solving construction site-level unequal-area facility layout problems,” *Automation in Construction*, vol. 9, no. 2, pp. 217–226, Mar. 2000, doi: 10.1016/s0926-5805(99)00006-0.

[5] M. J. Mawdesley and S. H. S. Al-Jibouri, “Proposed genetic algorithms for construction site layout,” *Engineering Applications of Artificial Intelligence*, vol. 16, no. 5–6, pp. 501–509, Aug. 2003, doi: 10.1016/j.engappai.2003.09.002.

[6] S. O. Cheung, T. K. L. Tong, and C. M. Tam, “Site pre-cast yard layout arrangement through genetic algorithms,” *Automation in Construction*, vol. 11, no. 1, pp. 35–46, Jan. 2002, doi: 10.1016/s0926-5805(01)00044-9.

[7] K. C. Lam, X. Ning, and M. C.-K. Lam, “Conjoining MMAS to GA to Solve Construction Site Layout Planning Problem,” *Journal of the Construction Division and Management*, vol. 135, no. 10, pp. 1049–1057, Oct. 2009, doi: 10.1061/(asce)0733-9364(2009)135:10(1049).

[8] I. Papadaki and A. P. Chassiakos, “Multi-objective Construction Site Layout Planning Using Genetic Algorithms,” *Procedia Engineering*, vol. 164, pp. 20–27, Jan. 2016, doi: 10.1016/j.proeng.2016.11.587.

[9] E. Gharaie, A. Afshar, and M. R. Jalali, "Site layout optimization with ACO algorithm." *In Proceedings of the 5th WSEAS international conference on artificial intelligence, knowledge engineering and data bases*, Feb. 2006 pp. 90-94.

[10] K. Y. Lam, X. Ning, and T. Ng, “The application of the ant colony optimization algorithm to the construction site layout planning problem,” *Construction Management and Economics*, vol. 25, no. 4, pp. 359–374, May 2007, doi: 10.1080/01446190600972870.

[11] G. Calis and O. Yuksel, "A comparative study for layout planning of temporary construction facilities: optimization by using ant colony algorithms." *In Proceedings of the 13th International Conference on Computing in Civil and Building Engineering*, Nottingham, UK pp. 267, 2010.

[12] G. Calis and O. Yuksel, “An Improved Ant Colony Optimization Algorithm for Construction Site Layout Problems,” Journal of *Building Construction and Planning Research*, vol. 03, no. 04, pp. 221–232, Dec. 2015, doi: 10.4236/jbcpr.2015.34022.

[13] L. Liang and W. Chao, “The strategies of tabu search technique for facility layout optimization,” *Automation in Construction*, vol. 17, no. 6, pp. 657–669, Aug. 2008, doi: 10.1016/j.autcon.2008.01.001.

[14] R. Gholizadeh,. G. Amiri, and B. Mohebi, “An alternative approach to a harmony search algorithm for a construction site layout problem,” *Canadian Journal of Civil Engineering*, vol. 37, no. 12, pp. 1560–1571, Oct. 2010, doi: 10.1139/l10-084.

[15] H. Zhang and J. Wang, “Particle Swarm Optimization for Construction Site Unequal-Area Layout,” *Journal of the Construction Division and Management*, vol. 134, no. 9, pp. 739–748, Sep. 2008, doi: 10.1061/(asce)0733-9364(2008)134:9(739).

[16] L.-C. Lien and M.-Y. Cheng, “A hybrid swarm intelligence based particle-bee algorithm for construction site layout optimization,” *Expert Systems With Applications*, vol. 39, no. 10, pp. 9642–9650, Aug. 2012, doi: 10.1016/j.eswa.2012.02.134.

[17] P. M. Farmakis and A. P. Chassiakos, “Dynamic Multi-objective Layout Planning of Construction Sites,” *Procedia Engineering*, vol. 196, pp. 674–681, Jan. 2017, doi: 10.1016/j.proeng.2017.08.057.

EXPERIENCES OF COUNTRIES WITH THE ADOPTION OF THE BIM-BASED PERMIT PROCESS

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Abstract

Construction projects are revolutionized by the introduction of Building Information Modelling (BIM) in the construction industry. It changed the way projects are managed and executed as a collaborative approach to building design, construction, and management. A relatively new concept that has been adopted in several countries around the world is the BIM-based permit process. This process involves the use of BIM technology to optimize the permit process for construction projects. The traditional process of obtaining a building permit involves multiple stakeholders and numerous steps and is often handled using paper documents or digital file submissions. Inefficient building permit procedures are considered time-consuming and prone to errors. Additionally, the demand for building permits has increased due to rapid urbanization, placing more significant pressure on regulatory authorities. This paper presents an analysis of the experiences of countries where the BIM-based permit process has been implemented: Singapore, Norway, Estonia, Finland and Netherland. Reviewing the existing literature and case studies, the advantages and challenges of this method are presented. The benefits identified include increased efficiency, improved accuracy, and reduced costs and delays in the permit process. However, there are many challenges, such as resistance to change and legal support. The paper also highlights the importance of government policies, stakeholder collaboration, and adequate training and education in successfully implementing the BIM-based permit process. The study concludes that the BIM-based permit process has the potential to improve the permit process for construction projects significantly, but its success depends on various factors.

Keywords: Building Information Modelling, building permit, compliance checking, case study.

1. Introduction

Construction projects are revolutionised by introducing BIM (Building Information Modelling) in the construction industry. It changed how projects are managed and executed as a collaborative approach to building design, construction, and management [1], [2]. Construction is currently the least digitised and industrialised of all industries. However, at the same time, it has the most opportunities and a comprehensive range of directions in which it can progress. What started digitisation is the emergence of all modern technologies. They are applied to some extent in construction projects, and BIM technologies are the most prominent [3].

According to the definition from the "National Building Information Modelling Standard" [4], the adequate description of the BIM is: "*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 decisions during its lifecycle from inception onward*". Although BIM technologies are emerging fast in the AEC (Architecture, Engineering & Construction) industry, a common problem is its implementation in public institutions and the processes of obtaining specific permits and legal documents. These processes are responsible for delays at the very beginning of the project, along with frequent errors and a large amount of human work. The issuance of building permits is considered one of the leading indicators for measuring a country's business [5].

Obtaining a building permit is a complex process involving the cooperation of many stakeholders through multiple steps [6]. In many countries, this process needs to be updated - where the paper format of documents is still used, with a low share of digitisation and process optimisation. Many governments are handling digital documents on different e-platforms, but still with a high range of manual work prone to errors and delays in the construction process. Rapid urbanisation has also led to an increased need for digitalisation, setting pressure on local authorities by increasing the number of requests for building permits [7]. A large number of researches in the past few years aimed to define the factors affecting the implementation of BIM technologies. The most commonly identified factors are grouped into categories, including top management and leadership, a workflow of the processes, technology and software availability, people and skills, standards and legal requirements, collaboration and communication [8]. Analysing the processes in the cities of Finland and Estonia resulted in four key categories: technology, people, process and policies, with the highlighted following factors: compatibility with the building regulations and codes, government support and willingness of employees to use a BIM-based building permit process, potential time savings with code compliance checks, and level of information standardisation [9]. In addition to affecting the speed of obtaining a building permit, these factors affect all processes during the facility's lifetime. Accordingly, it is necessary to work on their optimisation and digitisation urgently.

This paper presents an analysis of the experiences of countries where the BIM-based permit process has been implemented. Reviewing the existing literature, interviews with construction industry experts, reports and case studies, the advantages and challenges of this method are presented, together with the factors affecting adoption.

2. The concept of BIM-based permit process

Regarding the digitization of the construction permit system, it is possible to determine four primary levels of development. The first level is the system of issuing building permits in the outdated traditional way - on paper. Such a process is primarily inefficient and error-prone, leading to inconsistencies in estimates throughout the construction process. The second level refers to electronic building permit systems that are partially digitized, where building permit applications can be made online through documents in "pdf" format, allowing users to download forms and upload documents but not exploiting the full potential of digitization. A further step is complete digitization with interoperable machine-readable documents, modelling information about objects and automating processes in a BIM environment [10], [11].

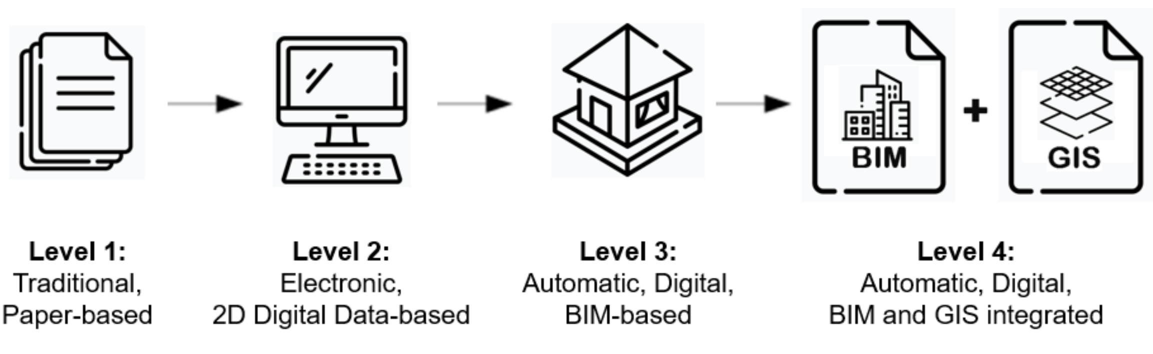

Fig. 1. Four levels of permit process development [12]

The fourth level represents the digitization of construction permits in the BIM environment integrating with GIS technologies for a more significant degree of automation. Both technologies can collect valuable data about the built environment. However, with different characteristics, special attention should be paid to their interoperability [13], [14].

2.1. Case studies of countries that have implemented the BIM-based permit process

Norway and Singapore have the highest degree of digitisation of construction permits, with projects that have been in practical use for over ten years and have undergone several revisions to meet current needs. The benefits of digitisation in construction permit systems include faster and more efficient processing of applications, reduced paperwork, and improved transparency [15]. In **Singapore**, the Building and Construction Authority's "*CORENET e-Submission system*" enables electronic submission and processing of construction permit applications in a centralised and standardised way. Singapore has made significant efforts to encourage the implementation of BIM to promote the adoption of BIM across the industry and improve productivity and quality. Since July 2015, architectural and engineering electronic submissions in BIM format have been mandatory for all new building projects with a gross floor area of over 5,000 m^2 [16]. In **Norway**, the Norwegian Building Authority developed "*ByggSøk*" and "*ByggNett*" project as solutions for verifying filled-in application forms related to specific types of applications. "*ByggSøk*" is an online application portal for building permits that enable applicants to submit and process their applications electronically. "*ByggNett*" is a web-based solution that provides access to information about building permits and other relevant regulations and standards [17].

Based on the 2021 report "Digitalisation of the construction sector" by the European Union, the level of digitalisation in the construction permit systems of member countries is provided. The report identifies five member states, Germany, Estonia, Netherlands, Austria, and Finland, that have integrated BIM into their building permit systems, enabling an automated process with 3D models [10]. In **Estonia**, the project "*BIM-based process for building permits in Estonia*" was launched in collaboration with the Estonian Ministry of Economic Affairs and Communications, where 3D digital twin plays an essential role in forming and arranging the design of the built environment and checking all kinds of restrictions such as zoning plans, existing underground infrastructure, or noise barriers [18]. In **Finland**, over 60% of Finnish municipalities have joined the online service platform "*Lupapiste*," which enables digital interaction between citizens, companies, and authorities based on permits for the built environment. The pilot project, completed in 2018 after the success of the "*KIRA-digi*" project, showed that all the information required for issuing a building permit could be accessed and interpreted directly from the BIM model [19], [20]. In the **Netherlands**, several projects for digitising building permits have been launched recently, of which the "*EuroSDR GeoBIM*" project stands out. This project focuses on data integration, interoperability, data quality, and user requirements. The project team is working to develop best practices, guidelines, and tools that will enable the integration of geospatial and BIM data [13], [21], [22]. Twelve other countries have a digitised system of issuing construction permits without BIM, while only two countries still rely on a traditional paper-based system [10].

Software companies and governments worldwide are developing an automated code compliance checking platform, which, in addition to BIM and artificial intelligence, can analyse a building model against all relevant building, fire, or energy codes. Among the first are the governments of Singapore and the United States [23]. A model of an automated code compliance process is shown in Fig. 2.

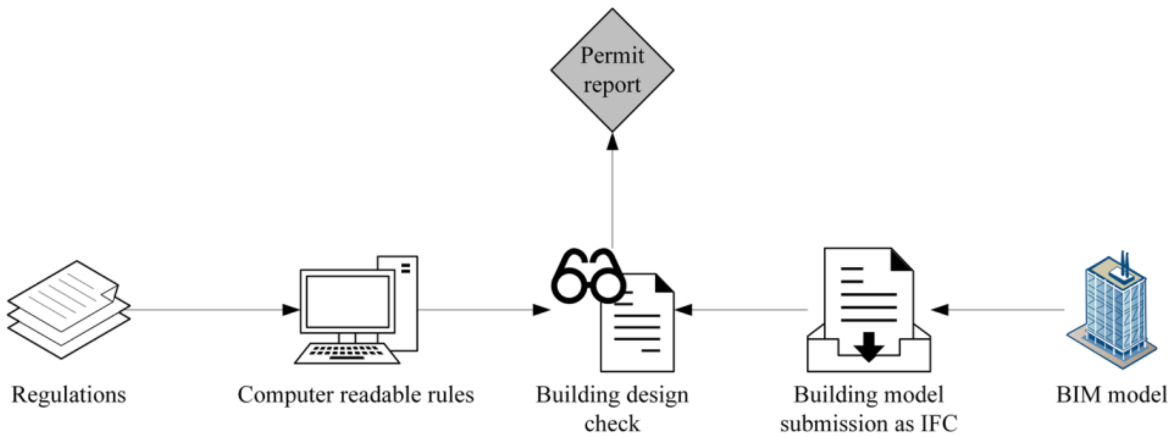

Fig. 2. The automatic code checking process that is based on BIM [23]

The United Kingdom has formed a network for digitising Requirements, Regulations, and Compliance Checking Processes in the Built Environment - Digital COMpliance (D-COM). In 2019 they accomplished a state-of-the-art review describing academic and industry implementations of "Automated compliance checking" (full and partial implementations). This document sets out the UK's goals for progress until 2025, the target date for the public sector adoption of openBIM (Fig. 3.). The importance of digitalisation is emphasised, given that the traditional way of checking takes time and increases costs and errors. This plan recommends a step-by-step approach, starting with the engagement of all stakeholders in the project, piloting, industrialisation and community outreach. In order to fulfil the goal, constant progress, government support and funding from the state are needed [24].

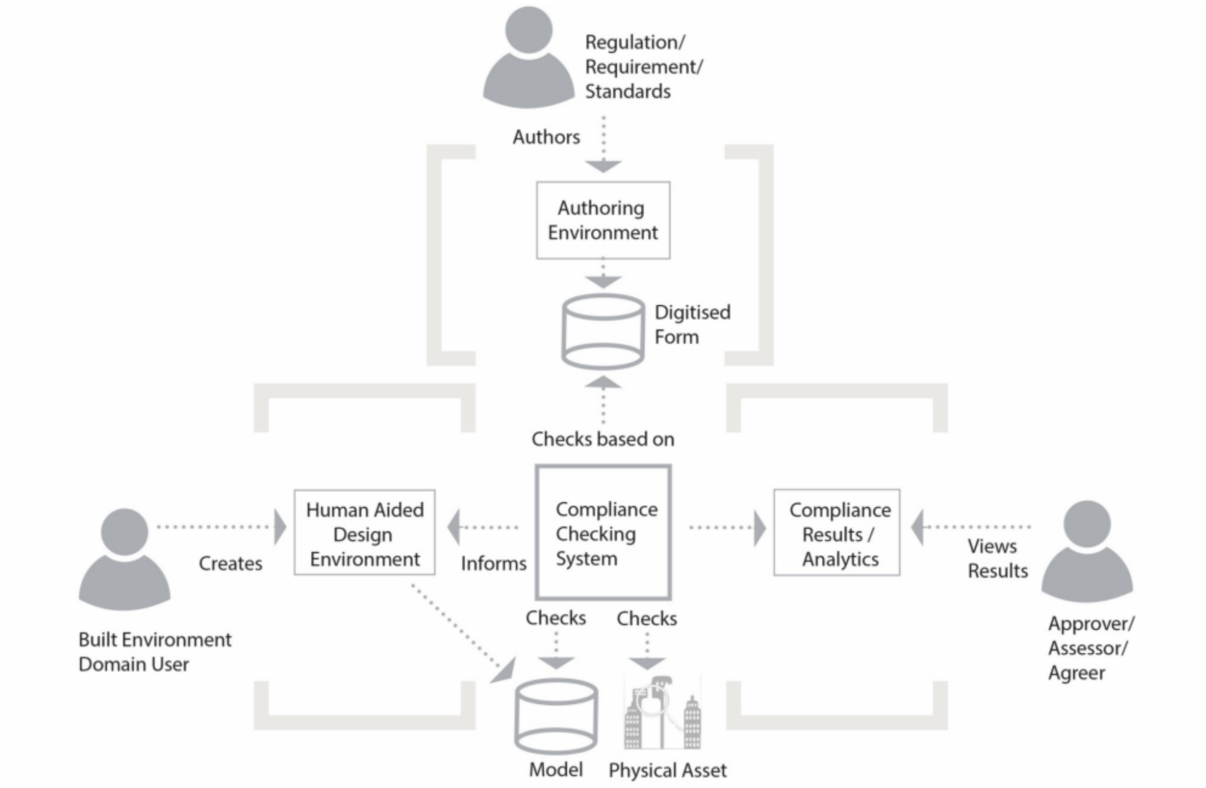

Fig. 3. Proposed model of the automated compliance checking process - plan for 2025 [24]

3. Advantages of the BIM-based Permit Process

3D digital twin plays an essential role in forming and arranging the design of the built environment and checking all kinds of restrictions and codes. Reviewing research and case studies of mentioned countries showed the advantages of the BIM-based permit process presented in this chapter. The same advantages were defined by Noardo et al. [12], who did a literature review on BIM building permits, analysed case studies of various methods from different countries, and defined: increasing efficiency, transparency and reduced costs.

The electronic issuance of a construction permit significantly speeds up and simplifies the processes of construction projects. The optimisation was achieved by coordinating with modern international standards, technologies and practices for efficient construction project implementation. The benefits of digitisation in construction permit systems include faster and more efficient processing of applications, reduced paperwork, and improved transparency. A mechanism of transparency is ensured through the precise determination of procedures.

Increasing automation with less human work was proposed, involving BIM software and machine learning algorithms. This integration can reduce the manual work required to process applications, resulting in faster permit processing times and fewer errors. Increased levels of automation also help reduce costs and improve the accuracy of the permit application process [25]. Noardo et al. (2020) presented a method for semi-automating the project compliance process. The method was tested on a case study of the design of a residential building in Rotterdam, whose architectural model already existed, in order to best reflect the actual situation with BIM models in practice. The results show that it can successfully identify non-conforming design elements. The method can reduce the time and effort required for manual checks and improve the accuracy of the review process [26].

The data accuracy advantages follow the BIM environment that allows precise 3D models, which increases the accuracy of data on the object's geometry and its characteristics. The data validation system uses the rules defined in the legislation, which ensures that the data entered into the system is accurate and correct. Introducing BIM methodology into the building permit process also allows data to be updated in real-time during construction, ensuring data accuracy and reducing errors. Several mentioned studies have attempted to use artificial intelligence technology to extract the regulatory information necessary for automated code checking automatically. All these advantages contribute to greater accuracy of data in issuing construction permits, which can contribute to better planning and management of the construction of buildings [27].

4. Challenges of the BIM-based Permit Process

The adoption of BIM in the building permitting process has the potential to improve the AEC industry significantly. However, some fundamental challenges are being faced - current technical deficiencies and the need for standardization and digitization of technical regulations. Due to the many different regulations in each country, with the frequent updating of the regulations, developing an automatic code-checking system requires significant work. Eventually, the overall efficiency of a construction project depends heavily on the actions and decisions of the authority.

Resistance to change involves difficulties in convincing stakeholders to adopt new technologies or processes. At the same time, the lack of legal support and government policies relates to the need for more explicit guidelines and frameworks to guide its implementation. The paper emphasizes the importance of cooperation between the client, the architect, the engineer and the local authorities responsible for issuing the building permit. A collaborative approach also reduces errors and delays in the permit application process [28], [29].

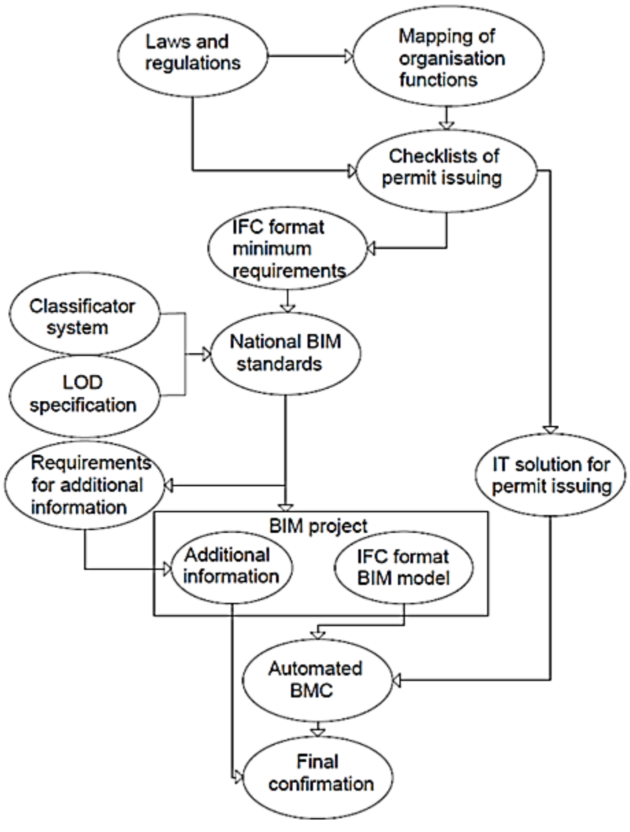

Fig. 4. The business model for Talin City Government [30]

A new business organization model must be developed for successful BIM adoption, as it was for the Talin City Government. Talin's business model is shown in Fig. 4., and had the primary task of mapping the functions of the departments involved in the permit-issuing process. It enables the creation of detailed checklists for comparing relevant application parameters against the national building code. Nevertheless, it all depends on if the submitted BIM project is standardized. Therefore, it is necessary to create national BIM standards, including precise IFC format minimum requirements [30]. Based on the experience of the existing methods, to use the verification system, it is necessary to increase the quality of human work by improving the training and education of the involved participants. Such an improved model would be a helpful input and a first step towards further developing tools for automatic model validation, following more apparent constraints, definitions and criteria.

5. Conclusion

The emergence of all modern technologies, primarily BIM, has triggered much research and proposed methods. A common problem is implementing BIM in public institutions and obtaining specific permits and legal documents. The issuance of building permits plays an essential role in the AEC industry and is the leading indicator for measuring a country's business. This process needs to be updated in many countries, with a low share of digitisation and process optimisation.

The paper analyses the application of Building Information Modelling technology in issuing building permits to optimise a process that is often time and financially demanding, with many users and steps involved. Using BIM requires the cooperation of all stakeholders and can reduce the amount of paperwork and errors that occur in the process. Integrating BIM software and machine learning algorithms, manual work can be reduced, contributing to greater data accuracy in issuing construction permits. Advantages include increased efficiency, improved accuracy, reduced costs, and delays in obtaining permits. In contrast, challenges include the establishment of standardisation and digitisation of technical regulations, resistance to change, and the necessity of training participants in the process. However, success depends on various factors, adequate support from the authorities, and all stakeholders' cooperation. The paper presents the experiences of countries that have applied this method: Singapore, Norway, Estonia, Finland and the Netherlands.

The study concludes that the BIM-based permit process has the potential to improve the permit process for construction projects significantly, but its success depends on various factors. The most commonly identified factors affecting adoption are grouped into categories: top management and leadership, a workflow of the processes, technology and software availability, people and skills, standards and legal requirements, collaboration and communication. The directions for further research have a wide range, but what needs to be improved in the current research are methods and guidelines on practically applying all proposed methods in public institutions and defining the application's precise steps and algorithm.

Acknowledgements

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References

[1] ‘Supporting digitalisation of the construction sector and SMEs Including Building Information Modelling’, 2019, doi: 10.2826/422658.
[2] ‘Foreword 3 Introduction 4’, 2021.
[3] S. O. Abioye et al., ‘Artificial intelligence in the construction industry: A review of present status, opportunities and future challenges’, Journal of Building Engineering, vol. 44. Elsevier Ltd, Dec. 01, 2021. doi: 10.1016/j.jobe.2021.103299.
[4] N. Committee and N. Authors, ‘National Building Information Modeling Standard Version 1 - Part 1: Overview, Principles, and Methodologies’, 2007.
[5] World Bank Group. and World Bank., Doing business 2020 : comparing business regulation in 190 economies.
[6] G. Yilmaz, A. Akcamete, and O. Demirors, ‘BIM-CAREM: Assessing the BIM capabilities of design, construction and facilities management processes in the construction industry’, Comput Ind, vol. 147, May 2023, doi: 10.1016/j.compind.2023.103861.

[7] K. Ullah, E. Witt, and I. Lill, 'The BIM-Based Building Permit Process: Factors Affecting Adoption', Buildings, vol. 12, no. 1, Jan. 2022, doi: 10.3390/buildings12010045.
[8] L. Liao and E. A. L. Teo, 'Managing critical drivers for building information modelling implementation in the Singapore construction industry: an organizational change perspective', International Journal of Construction Management, vol. 19, no. 3, pp. 240–256, May 2019, doi: 10.1080/15623599.2017.1423165.
[9] K. Ullah, E. Witt, I. Lill, N. Banaitienė, and M. Statulevičius, 'READINESS ASSESSMENT FOR BIM-BASED BUILDING PERMIT PROCESSES USING FUZZY-COPRAS', Journal of Civil Engineering and Management, vol. 28, no. 8, pp. 620–633, Sep. 2022, doi: 10.3846/jcem.2022.17274.
[10] European Construction Sector Observatory, 'Digitalisation in the construction sector - Analytical Report', 2021.
[11] F. Noardo et al., 'INTEGRATING EXPERTISES and AMBITIONS for DATA-DRIVEN DIGITAL BUILDING PERMITS - The EUNET4DBP', in International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences - ISPRS Archives, International Society for Photogrammetry and Remote Sensing, Sep. 2020, pp. 103–110. doi: 10.5194/isprs-archives-XLIV-4-W1-2020-103-2020.
[12] F. Noardo et al., 'Unveiling the actual progress of Digital Building Permit: Getting awareness through a critical state of the art review', Build Environ, vol. 213, p. 108854, Apr. 2022, doi: 10.1016/J.BUILDENV.2022.108854.
[13] F. Noardo, T. Wu, K. Arroyo Ohori, T. Krijnen, H. Tezerdi, and J. Stoter, 'Geobim for digital building permit process: Learning from a case study in Rotterdam', in ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Copernicus GmbH, Sep. 2020, pp. 151–158. doi: 10.5194/isprs-annals-VI-4-W1-2020-151-2020.
[14] K. A. Ohori, A. Diakité, T. Krijnen, H. Ledoux, and J. Stoter, 'Processing BIM and GIS models in practice: Experiences and recommendations from a GeoBIM project in The Netherlands', ISPRS Int J Geoinf, vol. 7, no. 8, Aug. 2018, doi: 10.3390/ijgi7080311.
[15] E. Hjelseth, 'Public BIM-based model checking solutions: lessons learned from Singapore and Norway', in Building Information Modelling (BIM) in Design, Construction and Operations, WIT Press, Sep. 2015, pp. 421–436. doi: 10.2495/bim150351.
[16] Singapore Government, 'CORENET'. https://www.corenet.gov.sg/general/building-information-modeling-(bim)-e-submission.aspx (accessed Mar. 09, 2023).
[17]. 'R2014 - ByggNett Status Survey'.
[18] R. Klooster, J. Van Deth, L. Van Berlo, and S. Meijer, 'Be bold est'.
[19] European Construction Sector Observatory, 'Finland - Digital Building Permit Process Using BIM Thematic objective 4', 2021.
[20] 'KIRA-Digi'. http://www.kiradigi.fi/en/front-page.html (accessed Mar. 09, 2023).
[21] K. A. Ohori, T. Krijnen, A. Diakité, H. Ledoux, and J. Stoter, 'GeoBIM project Final report', 2018.
[22] F. Noardo et al., 'EuRoSDR GeoBIM project a study in Europe on how to use the potentials of BIM and GEO data in practice', in International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences - ISPRS Archives, International Society for Photogrammetry and Remote Sensing, 2019, pp. 53–60. doi: 10.5194/isprs-archives-XLII-4-W15-53-2019.
[23] D. Guler and T. Yomralioglu, 'Reviewing the literature on the tripartite cycle containing digital building permit, 3D city modeling, and 3D property ownership', Land use policy, vol. 121, Oct. 2022, doi: 10.1016/j.landusepol.2022.106337.
[24] Centre for Digital Built Britain, 'Digital COMpliance D-COM: Digitisation of Requirements, Regulations and Compliance Checking Processes in the Built Environment Final Report'.
[25] K. Battisti et al., 'An Automatic Process for the Application of Building Permits', Buildings, vol. 13, no. 1, Jan. 2023, doi: 10.3390/buildings13010078.
[26] F. Noardo, T. Wu, K. Arroyo Ohori, T. Krijnen, and J. Stoter, 'IFC models for semi-automating common planning checks for building permits', Autom Constr, vol. 134, Feb. 2022, doi: 10.1016/j.autcon.2021.104097.
[27] I. Kim, J. Choi, E. A. L. Teo, and H. Sun, 'Development of kbim e-submission prototypical system for the openbim-based building permit framework', Journal of Civil Engineering and Management, vol. 26, no. 8, pp. 744–756, Nov. 2020, doi: 10.3846/jcem.2020.13756.
[28] K. Sulonen and J. Vastamäki, 'Improving efficiency in Finnish public land use processes – regulatory change and digitalisation in focus', Nordic Journal of Surveying and Real Estate Research, vol. 16, no. 1, Jan. 2022, doi: 10.30672/njsr.49388.
[29] H. Lee, J. K. Lee, S. Park, and I. Kim, 'Translating building legislation into a computer-executable format for evaluating building permit requirements', Autom Constr, vol. 71, pp. 49–61, Nov. 2016, doi: 10.1016/j.autcon.2016.04.008.
[30] K. Ullah, C. Raitviir, I. Lill, and E. Witt, 'BIM adoption in the AEC/FM industry – The case for issuing building permits', International Journal of Strategic Property Management, vol. 26, no. 4, pp. 400–413, Oct. 2020, doi: 10.3846/ijspm.2020.13676.

EXPLORING ESSENTIAL CHANGE PRACTICES FOR THE SUCCESSFUL EXECUTION OF ORGANIZATIONAL CHANGE EFFORTS IN CAPITAL PROJECT ORGANIZATIONS

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Abstract
The past few years have brought major disruptions to historically stable industries. Events such as the COVID-19 pandemic, labor shortages, low-carbon initiatives, and infrastructure investments have been driving organizations to rethink their current-traditional ways and models of conducting business, and in turn, initiating major organizational change efforts. The capital projects industry is no exception, as capital project organizations are dealing with an endlessly changing environment that is continuously destabilizing the design, construction, delivery, operation, and management of capital projects. Thus, to remain successful in this changing environment, capital project organizations need to properly plan and successfully execute their change efforts. As such, the objective of this study is to investigate change practices that can be essential in supporting the successful execution of organizational change efforts and allowing organizations to effectively adapt to changing environments. To achieve the desired objective, a three-step methodology was adopted. First, a series of interviews were conducted with capital project organizations to learn about their past and ongoing organizational change efforts. Next, thematic analysis was employed to code common themes and identify the utilized change practices. The practices were then defined using the existing research corpus. The methodology resulted in a set of 60 change practices that are presented and defined in this paper. The findings of this study can be important for industry practitioners as they can use the change practices in planning and executing their change efforts, as well as researchers who can build on the change practices when investigating organizational change both inside and outside the capital projects industry.

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Keywords: capital projects, change efforts, change management, change practices, organizational change.

1. Introduction

The capital projects industry plays a crucial role in developing and maintaining complex and large-scale projects that are essential for economic growth and development such as highways, airports, and power plants [1]. For the past few years, the industry has been navigating a rapidly changing environment that is fueled by multiple factors such as an aging workforce [2], labor shortage [3], technological advancements [4], aging infrastructure [5], and environmental legislation on carbon emissions [6] and resource efficiencies [7].

To adapt to these changes, capital project organizations have been undergoing organizational change efforts to transform their traditional business practices [8], and such efforts have significantly accelerated after the COVID-19 pandemic [9]. In fact, the majority of industry leaders and decision-makers recognize the need to rethink the current state of conducting business [10]. This recognition also comes at a time when global capital project spending is projected to reach 130 trillion dollars globally by 2027 to decarbonize and renew critical infrastructure, thereby creating vast opportunities for capital project organizations to seize market opportunities and generate profit [6].

1.1. Point of Departure and Objective

To understand the dynamics of organizational change in the capital projects industry, and upon building on organizational change studies, three major aspects need to be considered [11]:

- Drivers for change, i.e. the factors that characterize the changing environment and drive an organization to undergo change efforts.
- Response to change, i.e. the resulting decisions and actions an organization implements in response to the changing environment and change drivers to adapt and achieve the desired outcome.
- Challenges facing change, i.e. the obstacles that the organization can face and need to overcome for a successful organizational change implementation.

Thus, the objective of this paper is to identify and define change practices that can play a critical role in the success of change efforts.

2. Methodology

To achieve the desired objective, this paper adopts a three-step methodology.

2.1. Identifying capital organizations and conducting interviews

A total of 11 semi-structured interviews were conducted with 10 capital project organizations as described in Table 1. The semi-structured approach offers researchers flexibility when gaining insights and developing an understanding of industry-related topics especially when dealing with large industries, different types of organizations, and topics that have not been extensively discussed before [12]–[15]. The companies chosen were either “owner” or “contractor” as they play a pivotal role in the value chain of capital projects [10]. According to [16], [17]:

- Owner capital project organizations can be defined as social structures that pursue and manage a collection of capital projects in support of the company strategy and possess the authority and independence to make decisions and drive change.
- Contractor capital project organizations can be defined as social structures that manage a collection of capital projects that align with both the owner's and their own company’s strategies and possess the autonomy and power to make decisions and enact change.

Interviewing the two big players can provide a holistic understanding of organizational change within the capital projects industry. Thus, the authors and a Task Force of 15 industry practitioners created a list of candidate organizations from different sectors to interview. This list included owner and contractor capital project organizations that were known to have recently undergone an organizational change.

The semi-structured interviews focused on four main aspects: the organization’s background information, the organization’s current capabilities, the organization’s future direction, and the investigated change effort in terms of drivers, response, and challenges. It should be noted that the authors delve into the various aspects of drivers (i.e., the weight of the past, the push of the present, and the pull of the future), reponse, and challenges (i.e, across strategy, structure, people and culture, process and technology). The results presented in this paper, however, outline the results from a high level only, i.e., practices associated with drivers, responses, and challenges.

2.2. Performing content analysis

Content analysis can be defined as a "research technique for making replicable and valid inferences from texts or other meaningful matter to the contexts of their use" [18]. It is a regularly used technique in research to interpret raw data collected from interviews and systematically convert it into concise key results [19], [20]. Content analysis can be summarized in four main stages [19], [21]: (1) *condensation* or condensing interview transcripts by reading, evaluating, removing unnecessary information, and eliminating ambiguities; (2) *coding* where condensed units that share the same meaning or insights are assigned to a "code" or a label that is generally made up of one to two words; (3) *categorization* by grouping or clustering codes that are "related through content or context"; and (4) *theme* that communicates the underlying meaning of the clustered categories. The "Nvivo" software was used to perform the analysis. A total of 60 themes were generated as a result of the content analysis, where each theme represents a unique "change practice". The generation of these themes is illustrated in Fig. 1 which shows how many new change practices were generated after analyzing the content of every interview transcript (for example: "17 new themes" in "B" means that 11 new change practices were identified after analyzing Case study B in addition to the 33 change practices that were firstly identified in Case Study A). Fig. 1 also shows that the study achieved "theoretic data saturation" where the data no longer generated new themes as more interviews were analyzed [22]. This indicates that the 11 case studies performed were enough to identify the common change practices and no further case studies were needed.

Table 1. Description of case studies.

Case Study	Company Size	Company Type	Company Age	Interviews and Interviewees	Change Description
A	1-1,000 employees	Owner	More than 100 years	4 Interviews 6 Interviewees	New Market (implications of Lithium growth opportunities for the company)
B	More than 10,000 employees	Contractor	More than 100 yearsChevron, more than 10,	2 Interview 1 Interviewee	Digitization (implications of digitization on EPC operations)
C	More than 10,000 employees	Owner	More than 100 years	1 Interview 2 Interviewees	Execution Model (implications of a new capital projects operating model)
D	More than 10,000 employees	Owner	25-50 years	1 Interview 1 Interviewee	Remote Working (implications of remote work on an airport authority)
E	More than 10,000 employees	Contractor	More than 100 years	1 Interview 1 Interviewee	New Market (implications of new market segment shift on an EPC business)
F	More than 10,000 employees	Owner	More than 100 years	1 Interview 1 Interviewee	Execution Model (implications of the adoption of integrated project delivery on the company's execution model)
G1	More than 10,000 employees	Owner	50-100 years	1 Interview 2 Interviewees	Execution Model (implication of public-private partnerships on the agency) execution model implications of new support
G2	More than 10,000 employees	Owner	50-100 years	1 Interview 2 Interviewees	Execution Model (implications of a new support model on the agency)
H	5,001-10,000 employees	Owner	25-50 years	1 Interview 1 Interviewee	Acquisition (implications of acquisition on a power generating company)
I	More than 10,000 employees	Owner	More than 100 years	1 Interview 1 Interviewee	Low Carbon Shift (implications of the market shift to low carbon on the company)
J	More than 10,000 employees	Owner	25-50 years	1 Interview 1 Interviewee	Low Carbon Shift (implications of the low carbon future on EPC operations)

2.3. Presenting Definitions from Literature

After identifying all change practices, each of them was defined using the existing body of knowledge. This step was critical to ensure consistency in the interpretation of the themes. Academic papers (journal and conference), books, and blogs were reviewed to extract definitions that explain each theme.

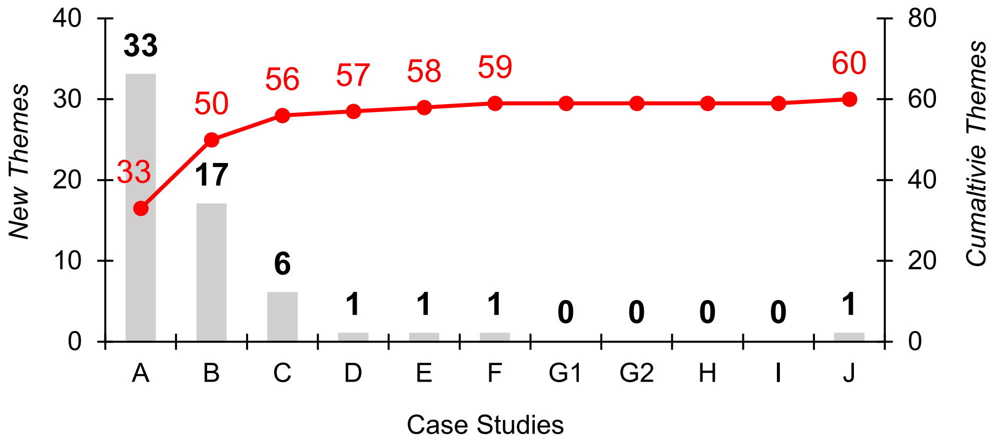

Fig. 1. The total number of "new themes" generated after analyzing the transcript of every case study and the cumulative total.

3. Results

The 60 themes identified from the content analysis are shown in Fig. 2. The "frequency" indicates the total number of codes that related to the theme when analyzing the interview content in regards to drivers, response, and challenges.

Moreover:

- For drivers for change, *Market Shift* (19) was the most common change practice, followed by *Resistance to Change* (12), *Nature of Industry* (9), *Client/Owner Needs* (7), and *Market Expansion* (6).
- For *response to change*, *Restructuring* (20) and *Communication* (20) were the most common change practices, followed by *Training* (18), *Partnerships* (17), and *Recruitment* (16).
- For challenges facing change, *Resistance to Change* (17) was the most common change practice, followed by *Retaining Workforce* (13), *Nature of Industry* (9), *Restructuring* (7), and *Training* (6).

Frequency	Change Practices	Drivers	Response	Challenges
29	Restructuring	2	20	7
29	Resistance to change	12		17
28	Communication	3	20	5
25	Training	1	18	6
23	Market shift	19	1	3
23	Partnerships	2	17	4
19	Nature of industry	9	1	9
19	Supportive leadership	2	13	4
17	Internal capabilities	4	12	1
17	Organizational design	4	8	5
17	Recruitment		16	1
16	Market expansion	6	9	1
16	Organizational commitment	5	8	3
15	Resources	3	7	5
15	Retaining workforce		2	13
13	Clients/owners needs	7	2	4
13	Integration		11	2
13	Portfolio	5	6	2
13	Remote work	4	6	3
12	Shift in the required skillset	3	5	4
12	Strategic objective	2	8	2
12	Technology	2	10	
11	Anticipation	1	10	
11	Human resource allocation		8	3
9	Operating model	4	2	3
9	Project execution		7	2
8	Reporting		7	1
8	Sustainability	7		1
7	External interactions	1	5	1
7	Process re-engineering		4	3

Frequency	Change Practices	Drivers	Response	Challenges
7	Regional/unit requirements	2		5
6	Feedback collection		6	
6	Network		4	2
5	Competitive advantage	3	2	
5	Digitization	3	2	
5	Diversity and inclusion		5	
5	Effective leadership		5	
5	External/internal benchmarking		5	
5	Gov't participation/control/support	4		1
5	Knowledge management		5	
5	Leadership changes	1	4	
5	Relationships with private and public entities		5	
5	Resource efficiency		5	
5	Termination		5	
5	Workforce	1	1	3
4	Accountability		4	
4	Owner/client requirements	1	1	2
4	Subs and suppliers adaptability	3	1	
3	Career progression		3	
3	Competitive bids	1		2
3	Continuous improvement		2	1
3	Innovation		3	
3	Research and development		2	1
3	Scaling	1	1	1
3	Stage-gate processes		3	
2	Adaptive changes		2	
2	Budget		1	1
2	External growth opportunities		2	
2	Investment		2	
1	Metrics		1	

Fig. 2. The resulting change practices (i.e. themes) and their distribution between "Drivers", "Response", and "Challenges".

Table 1. The definition of coded "change practices" from literature.

Change Practice	Definition
Accountability	The extent to which one's actions are evaluated by an external constituency that has relevant rewards or punishment. A process that activates when personnel reaches a state which the authoritative entity within the organization wishes to hold them to account for [23], [24].
Adaptive changes	Small, incremental changes that organizations and managers create to adapt to business challenges. These changes aim to improve existing processes rather than altering the organization as a whole [25].
Anticipation	An organization attempts to manage its future activities and shape its surroundings. Not the simple unfolding of events, but rather anticipatory activities that serve to gauge and guide the organization's future actions [26].
Budget	A financial plan for a defined period that includes costs and expenses, assets, liabilities, and cash flows of an organization. A sum of the finances allocated for a particular purpose [27].
Career progression	Advancement in an employee's level of position and/or level of reward within an organization [28].
Clients/owners' needs	A high-level representation of the clients' or owners' requirements to solve a problem or achieve an objective [29].
Communication	Sending and receiving information through different formats (e.g., oral, written, electronic). Can occur at different levels (unit, department, enterprise), in different forms (formal, informal), and within or outside the organization [30].
Competitive advantage	Factors that allow an organization to deliver its services better and more cost-effectively than its rivals. This relates to the financial, strategic, and technological capabilities of the organization [31].
Competitive bids	The process through which a group of organizations competes to win a bid from a client to deliver a project at a particular point in time and for a specified cost [32].
Continuous improvement	Ongoing efforts to improve services or processes within an organization [33].
Digitization	The process of connecting different systems with the value chain of an organization. Working with digital tools and different technologies to improve organizational workflow [34], [35].
Diversity and inclusion	Achievement of a work environment in which all individuals from a variety of individual values, races, and beliefs are treated fairly and respectfully, all have equal access to opportunities and resources, and all can contribute to the organization's success [36]
Effective leadership	Strong leaders communicate a change initiative message throughout the organization [37], [38].
External growth opportunities	Leveraging external relations with existing clients to facilitate growth [39].
External interactions	An organization's decision to partner and interact with external entities (whether local, international, or governmental) to achieve its organizational strategy [39].
External/internal benchmarking	A systematic process of measuring an organization's performance against recognized peers to evaluate current status. Determining best practices that can lead to superior performance when utilized [40].
Feedback collection	An organization's collection of feedback about current or future organizational changes [41].
Government participation/ control/ support	Exposure to policy changes and a wide range of government involvement can happen through enforced laws or collaboration [42].
Human resource allocation	The process of assigning and managing resources (people) to support an organization's strategic goals [43].
Innovation	The search for, the discovery of, development, improvement, adoption, and commercialization of new processes, new products, and new organizational structures and procedures to achieve short- and long-term goals, improve productivity, and increase profitability [44], [45].
Integration	The extent to which distinct and interdependent organizational components constitute a unified whole [46].
Internal capabilities	Organizational characteristics that enable an organization to conceive, choose, and implement strategies. Capabilities could include product innovations and responsiveness to market trends and marketing [47].
Investment	The allocation of resources of any kind and purpose that is relevant to the organization [48].
Knowledge management	Protected and unprotected knowledge creation and transfer through various means, such as face-to-face interactions (planned or ad hoc), mentoring, job rotation, and staff development [49], [50].

Table 2. The definition of coded “change practices” from literature (continued).

Change Practice	Definition
Leadership changes	Changes to a leadership position within an organization (at the unit or corporate level) that occur as a result of an organizational restructuring process, financial losses, attrition, or layoffs [51].
Market awareness	Entering a new market (i.e., geographic, demographic) to sell existing products or services) [52].
Market shift	Significant and permanent changes in market needs and behaviors [53].
Metrics	Quantifiable measures are used to track and assess the status of a specific organizational process or performance [54].
Nature of industry	Essential qualities or characteristics that an industry is known for (e.g., fragmentation in the AEC industry) [55].
Network	A social structure is made up of a set of social actors (people or organizations) that interact with each other [56].
Operating model	A model that describes how an organization delivers and achieves value for owners, customers, and itself [57], [58].
Organizational commitment	The act of pledging or promising to fulfill an obligation to the organization. A strong belief in the organization’s goals and values [59].
Organizational design	A set of actions taken by an organization to shape the way it operates. Aims to integrate people, strategy, structure, and technology [60].
Owner/client requirements	A condition or capability that clients or owners require to solve a problem or to achieve an objective (the need) [61].
Partnerships	An ongoing collaborative relationship between two or more legally separated organizations is based on a commitment to share the costs, risks, and rewards derived from working together [62].
Portfolio	A group of projects and services that an organization manages together to coordinate interfaces and prioritize resources, thereby reducing uncertainty in their execution and helping the organization achieve its strategic goals [63].
Process re-engineering	The analysis and redesign of workflows and processes within an organization, to enhance and streamline business structures, processes, management systems, and external relationships to deliver value [61].
Project execution	Performing project activities and scopes of work following project plans and specifications [64].
Recruitment	A process that provides the organization with a pool of qualified job candidates from which to choose [65].
Regional/unit requirements	A set of requirements is needed in an organization’s unit or by certain regions in which the organization operates [39].
Relationships with private and public entities	Collaboration between two organizations (private and/or public) to achieve business goals [66].
Remote work	The ability for employees of an organization to perform their jobs from a location other than the central office, often via communications technology [67].
Reporting	The process of compiling and reviewing the information within a specific functional area of an organization (e.g., operations), where performance is monitored and measured [68].
Research and development	Investments an organization makes in research and development to gain a technological and competitive advantage [69].
Resistance to change	Opposition by workforce and employees to an organizational change initiative that will change and/or disrupt the status quo [70].
Resource efficiency	Enhancing organizational resource utilization (e.g., people, assists, financials) to minimize waste such as idle time [71].
Resources	The tangible and intangible entities available to an organization enable it to efficiently and/or effectively produce a market offering that has value for some market segment or segment [72].
Restructuring	There are three types of restructuring: organizational, portfolio, and financial. Divestments, acquisitions, and/or mergers that involve two or more major businesses, including asset restructuring and internal management changes. The reconfiguration of an internal administrative structure is associated with an intentional management change program [44].
Retaining workforce	The actions an organization makes to retain workforce. This can include fostering a positive work atmosphere, providing competitive pay and incentives, and promoting employee engagement [73].
Scaling	The growth (scale up) of an organizational initiative/process. Can be horizontal (i.e., growth within an area of operation or region) or vertical (i.e., within the organization itself) [74].

Table 2. The definition of coded “change practices” from literature (continued).

Change Practice	Definition
Shift in the required skill set	Changes in the workers’ knowledge and skills requirements are driven by changes in the environment, technology, and market demand [75].
Stage-gate processes	A systematic process by which a change initiative is divided into distinct stages or phases to drive its transformation from idea to execution [76].
Strategic objective	Purpose statements create a vision and set goals with measurable steps to help an organization achieve a desired outcome [77].
Subs and suppliers’ adaptability	The ability for subcontractors or suppliers to adjust their structure and processes to successfully achieve their goals [78].
Supportive leadership	Leadership encourages various change initiatives at different levels within an organization [51].
Sustainability	Activities taken by an organization, whether voluntary or governed by law, demonstrate its ability to maintain viable business operations (including financial viability, as appropriate) while not negatively affecting any social or ecological systems. Meeting the needs of the present without compromising the ability of future generations to meet their own needs [79].
Technology	The total sum of manmade devices or processes that alter, refine, or create the new goods and services delivered by organizations. Includes electronics, software, documents, new techniques, or any combination thereof used in the delivery of services [80].
Termination	The end of an employee’s work with an organization, whether voluntary or involuntary. Involuntary termination can be defined as an employer-initiated decision to terminate an individual's employment at an organization based on a particular cause (e.g., downsizing, performance problems, or insubordination) [81].
Training	An intervention aimed at increasing the knowledge and capacities of individuals to cope better personally, work more effectively with others, and/or perform their jobs better to help an organization achieve its goals [82].
Workforce	People engaged in or available for work, either in a country or area or in a particular organization or industry. The workforce can be unionized or nonunionized [83].

4. Conclusions

The main objective of this paper is to identify and define change practices that can play a critical role in the success of change efforts within the capital projects industry. Case studies were conducted on contractor capital project organizations and owner capital project organizations via interviews to investigate what drives their change (i.e. drivers), how they respond to change (i.e. response), and the obstacles during the change effort (i.e. challenges). Upon performing content analysis on interview transcripts, a total of 60 change practices were identified, and each practice was then defined from existing literature. As the aim of this study was solely to identify and define the change practices, the next studies will quantitatively evaluate the change practices to understand their significance and how their importance varies across different types of change efforts, as well as organization characteristics (such as sizes, types, and age). Furthermore, the findings of this study have significant implications for industry practitioners and researchers in the field of organizational change. For practitioners, the change practices identified in the study can serve as a valuable resource in planning and executing change efforts in their organizations as they can adapt and apply the practices within their unique organizational contexts. Similarly, researchers can use the findings of the study as a foundation for investigating organizational change in other industries and contexts and develop new theories and models of change that can be applied across a range of organizational contexts.

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References

[1] A. Barone, "What Is a Capital Project? With Examples and How Funding Works," *Ivestopedia: Corporate Finance*, 2022. https://www.investopedia.com/terms/c/capital-project.asp

[2] E. Yang and C. Manoosingh, "Aging Workforce and Their Safety and Health Concerns in the Construction Industry," in *54th ASC Annual International Conference Proceedings*, Associated Schools of Construction, 2018, pp. 322–329.

[3] R. Quint, "Young Adults and the Construction Trades," National Association of Home Builders, 2017.

[4] R. G. Lawrence, "Technology will be key for contractors on IIJA jobs, say experts," *Construction Dive*, 2022. https://www.constructiondive.com/news/technology-will-be-key-for-contractors-on-iija-jobs-say-experts/618741

[5] M. van den Boomen, G. Leontaris, and A. R. M. Wolfert, "Replacement optimization of ageing infrastructure under differential inflation," *Constr. Manag. Econ.*, vol. 37, no. 11, pp. 659–674, 2019, doi: 10.1080/01446193.2019.1574977.

[6] S. Fuchs, H. Hatami, T. Huizenga, and C. Schmitz, "Here comes the 21st century's first big investment wave. Is your capital strategy ready?," *McKinsey & Company*, 2022. https://www.mckinsey.com/capabilities/operations/our-insights/here-comes-the-21st-centurys-first-big-investment-wave-is-your-capital-strategy-ready.

[7] M. U. Hossain, S. T. Ng, P. Antwi-Afari, and B. Amor, "Circular economy and the construction industry: Existing trends, challenges and prospective framework for sustainable construction," *Renew. Sustain. Energy Rev.*, vol. 130, p. 109948, 2020, doi: 10.1016/j.rser.2020.109948.

[8] H. Nassereddine, M. B. Hatoum, S. Musick, and M. E. Jazzar, "Implications of Digitization on a Construction Organization: A Case Study," in *Proceedings of the Creative Construction e-Conference 2022*, Budapest, Hungary: Budapest University of Technology and Economics, 2022, pp. 71–79. doi: 10.3311/CCC2022-011.

[9] B. Orzeł and R. Wolniak, "Digitization in the Design and Construction Industry—Remote Work in the Context of Sustainability: A Study from Poland," *Sustainability*, vol. 14, no. 3, 2022, doi: 10.3390/su14031332.

[10] S. Chandrasekaran *et al.*, "Capital Projects 5.0: Reimagining capital-project delivery," McKinsey & Company, 2021. [Online]. Available: https://www.mckinsey.com/capabilities/operations/our-insights/capital-projects-50-reimagining-capital-project-delivery

[11] M. El Jazzar, "Adapting Through Organizational Change in Capital Project Organizations," Theses and Dissertations--Civil Engineering., University of Kentucky, Lexington, KY, USA, 2022. doi: 10.13023/etd.2022.63

[12] J. Carruthers, "A Rationale for the Use of Semi-structured Interviews," *J. Educ. Adm.*, vol. 28, no. 1, 1990, doi: 10.1108/09578239010006046.

[13] C. Cronin, "Using case study research as a rigorous form of inquiry," *Nurse Res.*, vol. 21, no. 5, pp. 19–27, 2014, doi: 10.7748/nr.21.5.19.e1240.

[14] D. Magaldi and M. Berler, "Semi-structured Interviews," in *Encyclopedia of Personality and Individual Differences*, V. Zeigler-Hill and T. K. Shackelford, Eds., Cham: Springer International Publishing, 2018, pp. 1–6. doi: 10.1007/978-3-319-28099-8_857-1.

[15] N. Mathers, N. J. Fox, and A. Hunn, *Using Interviews in a Research Project*. in Trent Focus for Research and Development in Primary Health Care: Using Interviews in a Research Project. Trent Focus, 1998.

[16] C. R. Leana and H. J. van Buren, "Organizational Social Capital and Employment Practices," *Acad. Manage. Rev.*, vol. 24, no. 3, pp. 538–555, 1999, doi: 10.2307/259141.

[17] B. Senior, S. Swailes, and C. Carnall, *Organizational Change*, 6th ed. Pearson, 2020.

[18] K. Krippendorff, *Content Analsis: An Introduction To Its Methodology*, 2nd ed. Sage Publications, 2004.

[19] K. A. Hilu and M. A. Hiyassat, "Qualitative assessment of resilience in construction projects," *Constr. Innov.*, vol. ahead-of-print, no. ahead-of-print, Jan. 2023, doi: 10.1108/CI-10-2022-0265.

[20] H.-F. Hsieh and S. E. Shannon, "Three approaches to qualitative content analysis," *Qual. Health Res.*, vol. 15, no. 9, pp. 1277–1288, 2005, doi 10.1177/1049732305276687.

[21] C. Erlingsson and P. Brysiewicz, "A hands-on guide to doing content analysis," *Afr. J. Emerg. Med.*, vol. 7, no. 3, pp. 93–99, 2017, doi: 10.1016/j.afjem.2017.08.001.

[22] B. Saunders *et al.*, "Saturation in qualitative research: exploring its conceptualization and operationalization," *Qual. Quant.*, vol. 52, no. 4, pp. 1893–1907, Jul. 2018, doi: 10.1007/s11135-017-0574-8.

[23] G. R. Ferris, J. H. Dulebohn, D. D. Frink, J. George-Falvy, T. R. Mitchell, and L. M. Matthews, "Job and Organizational Characteristics, Accountability, and Employee Influence," *J. Manag. Issues*, vol. 21, no. 4, pp. 518–533, 2009.

[24] M. Baldoni, C. Baroglio, K. M. May, R. Micalizio, and S. Tedeschi, "Supporting Organizational Accountability Inside Multiagent Systems," in *AI*IA 2017 Advances in Artificial Intelligence*, F. Esposito, R. Basili, S. Ferilli, and F. A. Lisi, Eds., Cham: Springer International Publishing, 2017, pp. 403–417.

[25] HBS Online, "Common Types of Organizational Change and How to Manage Them," *Harvard Bussiness School*, 2020. https://online.hbs.edu/blog/post/types-of-organizational-change

[26] M. Flyverbom and C. Garsten, "Anticipation and Organization: Seeing, knowing and governing futures," *Organ. Theory*, vol. 2, no. 3, p. 26317877211020324, 2021, doi: 10.1177/26317877211020325.

[27] Louise Ross and Technical Information Service, "Budgeting," The Chartered Institute of Management Accountants (CIMA), Topic Gateway Series No. 27, 2008.

[28] L. K. Stroh, J. M. Brett, and A. H. Reilly, "All the right stuff: A comparison of female and male managers' career progression.," *J. Appl. Psychol.*, vol. 77, pp. 251–260, 1992, doi: 10.1037/0021-9010.77.3.251.

[29] J. Sammy, "Needs and Solutions, Requirements and Designs," *International Institute of Bussiness Analysis (IIBA)*, 2013. https://www.iiba.org/professional-development/knowledge-centre/articles/needs-and-solutions.

[30] K. A. Baker, "Chapter 13. Organizational Communication," 2002, pp. 1–15.

[31] D. Ulrich and D. Lake, "Organizational capability: creating competitive advantage," *Acad. Manag. Perspect.*, vol. 5, no. 1, pp. 77–92, 1991, doi: 10.5465/ame.1991.4274728.

[32] L. G. Crowley and D. E. Hancher, "Evaluation of Competitive Bids," *J. Constr. Eng. Manag.*, vol. 121, no. 2, pp. 238–245, 1995, doi: 10.1061/(ASCE)0733-9364(1995)121:2(238).

[33] W. R. Seed, *Transforming Design and Construction: A Framework for Change*. Lean Construction Institute, 2015.

[34] K.-S. Schober and P. Hoff, "Digitization in the Construction Industry: Building Eruope's Road to 'Construction 4.0,'" Roland Berger GmbH, Munich, Germany, 2016.
[35] P. Evans-Greenwood, R. Hillard, and P. Williams, "Digitalizing the construction industry: A case study in complex disruption," Delloitte Insights, 2021. Accessed: Apr. 24, 2023. [Online]. Available: https://www2.deloitte.com/us/en/insights/topics/digital-transformation/digitizing-the-construction-industry.html
[36] M. B. Hatoum, A. Ammar, H. Nassereddine, and G. Dadi, "Preparing Construction Employers for the Gen-Z Workforce: A Case Study," in *Proceedings of the 30th Annual Conference of the International Group for Lean Construction (IGLC30)*, Edmonton, Canada, 2022, pp. 808–819. doi: 10.24928/2022/0193.
[37] B. Palmer, M. Walls, Z. Burgess, and C. Stough, "Emotional intelligence and effective leadership," *Leadersh. Organ. Dev. J.*, vol. 22, no. 1, pp. 5–10, Jan. 2001, doi: 10.1108/01437730110380174.
[38] C. J. Fenimore, "Leadership Effectiveness," *Encyclopedia of Leadership*. SAGE Publications, Inc., 2004. doi: 10.4135/9781412952392
[39] J. P. Kotter, "Managing External Dependence," *Acad. Manage. Rev.*, vol. 4, no. 1, pp. 87–92, 1979, doi: 10.2307/257406.
[40] CII, "Benchmarking & Metrics," *Knowledge Base*, 2023. https://www.construction-institute.org/resources/knowledgebase/best-practices/benchmarking-metrics.
[41] S. J. Ashford and L. L. Cummings, "Feedback as an individual resource: Personal strategies of creating information.," *Organ. Behav. Hum. Perform.*, vol. 32, pp. 370–398, 1983, doi: 10.1016/0030-5073(83)90156-3.
[42] CII RT-181, "IR181-2 - Integrated Project Risk Assessment (IPRA), Version 2.0," Construction Industry Institute. Accessed: Apr. 24, 2023. [Online]. Available: https://www.construction-institute.org/resources/knowledgebase/best-practices/project-risk-assessment/topics/rt-181/pubs/ir181-2
[43] C. A. Maritan and G. K. Lee, "Resource Allocation and Strategy," *J. Manag.*, vol. 43, no. 8, pp. 2411–2420, 2017, doi: 10.1177/0149206317729738.
[44] J. Liao, "Corporate restructuring, performance and competitiveness: an empirical examination," *Compet. Rev. Int. Bus. J.*, vol. 15, no. 1, pp. 33–48, Jan. 2005, doi: 10.1108/cr.2005.15.1.33.
[45] F. Damanpour, "Organizational Innovation," *Oxf. Res. Encycl. Bus. Manag.*, 2017, doi: 10.1093/acrefore/9780190224851.013.19.
[46] H. Barki and A. Pinsonneault, "A Model of Organizational Integration, Implementation Effort, and Performance," *Organ. Sci.*, vol. 16, no. 2, pp. 165–179, 2005, doi: 10.1287/orsc.1050.0118.
[47] D. J. Collis, "Research Note: How Valuable Are Organizational Capabilities?," *Strateg. Manag. J.*, vol. 15, pp. 143–152, 1994.
[48] S. Beer and J. L. Casti, *Investment against Disaster in Large Organizations*. in System and Decision Sciences - Core (SDS). Laxenburg, Austria: International Institute for Applied Systems Analysis (IIASA) Research Memorandum, 1975. Accessed: Apr. 24, 2023. [Online]. Available: https://pure.iiasa.ac.at/500
[49] M. Alavi and D. Leidner, "Knowledge Management Systems: Issues, Challenges, and Benefits," *Commun. Assoc. Inf. Syst.*, vol. 1, no. 7, 1999, doi: 10.17705/1CAIS.00107.
[50] M. Henao-Calad, P. R. Montoya, and B. U. Ochoa, "Knowledge management processes and intellectual property management processes: an integrated conceptual framework," *AD-Minist.*, vol. 31, pp. 137–160, 2017, doi: 10.17230/ad-minister.31.8.
[51] I. Dafid, M. Indrasurya, and U. Christiono, "The actualization of leadership models adopted by field implementers that influencing the contractor employees' motivation and performance," *J. Appl. Eng. Sci.*, vol. 17, no. 4, pp. 555–566, 2019, doi: 10.5937/jaes17-21908.
[52] P. Kotler and K. L. Keller, *Marketing Management*. in Business & Economics. Hoboken, NJ: Prentice Hall International, Inc, 2009.
[53] RS Consluting USA, "Market Shifts – Stay Alert and Be Ready," *Richard's Blog On Marketing*, 2015. https://www.rsconsulting-usa.com/market-shifts-stay-alert-and-be-ready/ (accessed Apr. 24, 2023).
[54] J. Bladt and B. Filbin, "Know the Difference Between Your Data and Your Metrics," *Harvard Bussiness Review: Social Enterprise*, 2013. https://hbr.org/2013/03/know-the-difference-between-yo.
[55] G. Ofori, "Nature of the Construction Industry, Its Needs and Its Development: A Review of Four Decades of Research," *J. Constr. Dev. Ctries.*, vol. 20, no. 2, pp. 115–135, 2015.
[56] U. Can and B. Alatas, "A new direction in social network analysis: Online social network analysis problems and applications," *Phys. Stat. Mech. Its Appl.*, vol. 535, p. 122372, 2019, doi: https://doi.org/10.1016/j.physa.2019.122372.
[57] C. Zott, R. Amit, and L. Massa, "The Business Model: Recent Developments and Future Research," *J. Manag.*, vol. 37, no. 4, pp. 1019–1042, 2011, doi: 10.1177/0149206311406265.
[58] J. Dias *et al.*, "Introducing the Next-Generation Operating Model," McKinsey on Digital Services, 2017.
[59] G. A. Zangaro, "Organizational Commitment: A Concept Analysis," *Nurs. Forum (Auckl.)*, vol. 36, no. 2, pp. 14–21, 2001, doi: 10.1111/j.1744-6198.2001.tb01179.x.
[60] S. Hossain, M. H. Hasan, and F. Saleh, "Factors Affecting Organizational Design: A Study on the Selected Dimensions in the Bangladeshi Context," *Am. J. Manag.*, vol. 18, no. 4, Nov. 2018, doi: 10.33423/ajm.v18i4.183.
[61] M. B. Hatoum, H. Nassereddine, and F. Badurdeen, "Reengineering Construction Processes in the Era of Construction 4.0: A Lean-Based Framework," in *Proc. 29th Annual Conference of the International Group for Lean Construction (IGLC)*, Lima, Peru, 2021, pp. 403–412. doi: 10.24928/2021/0126.
[62] D. Chicksand, "Partnerships: The role that power plays in shaping collaborative buyer–supplier exchanges," *Ind. Mark. Manag.*, vol. 48, pp. 121–139, 2015, doi: 10.1016/j.indmarman.2015.03.019.
[63] R. Müller and T. Blomquist, "Analysis of Roles and Responsibilities of Program and Portfolio Managers," in *Proceedings of the Global Project and Manufacturing Symposium*, Siegen, Germany, 2004.
[64] T. Ryan and G. Mark, "Attaining Successful Construction Project Execution Through Personnel and Communication," *J. Constr. Eng. Manag.*, vol. 146, no. 9, p. 04020101, Sep. 2020, doi: 10.1061/(ASCE)CO.1943-7862.0001892.
[65] B. Ramadan, H. Nassereddine, T. R. B. Taylor, and P. Goodrum, "Impact of technology use on workforce performance and information access in the construction industry," *Front. Built Environ.*, vol. 9, 2023, doi: 10.3389/fbuil.2023.1079203.

[66] P. M. Schoenhard, "A Three-Dimensional Approach to the Public-Private Distinction," *Utah Law Rev.*, vol. 2008, no. 2, pp. 635–664, 2008.
[67] T. Galanti, G. Guidetti, E. Mazzei, S. Zappalà, and F. Toscano, "Work From Home During the COVID-19 Outbreak: The Impact on Employees' Remote Work Productivity, Engagement, and Stress," *J. Occup. Environ. Med.*, vol. 63, no. 7, pp. e426–e432, 2021, doi: 10.1097/JOM.0000000000002236.
[68] L. Usenko and I. Zenkina, "Modern Trends and Issues of Corporate Reporting Data Disclosure on Organization Activities," *Mediterr. J. Soc. Sci.*, vol. 7, no. 3, p. 212, May 2016.
[69] S. Someya, "The role of R & D in construction firms," Massachusetts Institute of Technology, Cambridge, MA, USA, 1992.
[70] E. B. Dent and S. G. Goldberg, "Challenging 'Resistance to Change,'" *J. Appl. Behav. Sci.*, vol. 35, no. 1, pp. 25–41, 1999, doi: 10.1177/0021886399351003.
[71] EPA Victoria, "How to improve resource efficiency in your business," *Lower your business's impact*, 2023. https://www.epa.vic.gov.au/for-business/how-to/lower-environmental-impact-business/improve-resource-efficiency-business
[72] C. Homburg, J. P. Workman, and O. Jensen, "Fundamental changes in marketing organization: The movement toward a customer-focused organizational structure," *J. Acad. Mark. Sci.*, vol. 28, no. 4, pp. 459–478, Sep. 2000, doi: 10.1177/0092070300284001.
[73] S. H. Mohd Kasmuri, Z. Ismail, R. Mohd Nordin, and N. Hashim, "A Systematic Review of Employee Turnover Antecedents in the Construction Industry," *Environ.-Behav. Proc. J.*, vol. 5, no. 13, pp. 65–73, Mar. 2020, doi: 10.21834/e-bpj.v5i13.2100.
[74] D. Van Doren, P. P. Driessen, H. Runhaar, and M. Giezen, "Scaling-up low-carbon urban initiatives: Towards a better understanding," *Urban Stud.*, vol. 55, no. 1, pp. 175–194, 2018, doi: 10.1177/0042098016640456.
[75] K. M. Salleh, N. Iisa Sulaiman, and K. N. Talib, "Globalization's Impact on Soft Skills Demand in the Malaysian Workforce and Organizations: What makes graduates employable?," in *Proceedings of the First UPI International Conference on Technical and Vocational Education and Training*, Bandung, Indonesia, 2010, pp. 210–215.
[76] A. F. Cooper, J. English, and R. Thakur, Eds., *Enhancing global governance : towards a new diplomacy?* Tokyo: UNU Press, 2002.
[77] M. Bou Hatoum, H. Nassereddine, and F. Badurdeen, "Towards a Canvas for Construction 4.0 Implementation in AECO Organizations," in *Proceedings of the Creative Construction e-Conference*, Budapest, Hungary: Budapest University of Technology and Economics, 2022, pp. 214–220. doi: 10.3311/CCC2022-028.
[78] V. Weerakkody, M. Janssen, and Y. K. Dwivedi, *Handbook of Research on ICT-Enabled Transformational Government: A Global Perspective.* 2009. [Online]. Available: doi.org/10.4018/978-1-60566-390-6
[79] A. Ammar, M. B. Hatoum, H. Nassereddine, and G. Dadi, "Synergies Between Construction 4.0 Technologies and Sustainable Construction: A Bibliometric Analysis," in *Proceedings of the Creative Construction e-Conference 2022*, Budapest, Hungary: Budapest University of Technology and Economics, 2022, pp. 365–370. doi: 10.3311/CCC2022-046.
[80] M. B. Hatoum, H. Nassereddine, and G. Dadi, "Factors Influencing the Adoption of Construction 4.0 Technologies by Departments of Transportation," in *International Conference on Transportation and Development (ICTD 2023)*, Austin, Texas: American Society of Civil Engineers, 2023.
[81] A. L. Rubenstein, J. D. Kammeyer-Mueller, M. Wang, and T. G. Thundiyil, "'Embedded' at hire? Predicting the voluntary and involuntary turnover of new employees," *J. Organ. Behav.*, vol. 40, no. 3, pp. 342–359, 2019, doi: 10.1002/job.2335.
[82] P. Budhwar *et al.*, "Organizing/theorizing: developments in organization theory and practice," *Manag. Res. News*, vol. 25, no. 8/9/10, pp. 1–193, Jan. 2002, doi: 10.1108/01409170210783368.
[83] R. K. Sokas, X. S. Dong, and C. T. Cain, "Building a Sustainable Construction Workforce," *Int. J. Environ. Res. Public. Health*, vol. 16, no. 21, 2019, doi: 10.3390/ijerph16214202.

EXPLORING THE IMPACT OF TECHNOLOGY ON HVAC COMMISSIONING PRACTICES

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Abstract

The primary method to ensure that systems are operating as designed is heating, venting and air conditioning (HVAC) commissioning, painstakingly stepping through a sophisticated process of running, testing, and verifying that the various components move, react, and respond in a way that fully utilizes the equipment and meets the environmental needs of the building occupants. The significant positive impact of technology on HVAC Commissioning is undisputed. Little research exists, however, on the field challenges and resource implications of rapid changes to HVAC components and control software for owners and contractors. This research explores solutions to the challenges that arise when advanced HVAC controls technology becomes burdensome and disadvantageous. The role of HVAC Commissioning within the very real constraints of federal mandates for energy use and the trend to convert from fossil fuels to “clean” fuels cannot be overlooked. The “trade-offs” encountered are substantial when highly sophisticated control sequences are utilized with HVAC equipment in the private sector and government facilities. The consequence of the lack of skilled technicians clearly has the opposite effect on utility savings. This research validates the effect of the practices of skilled professionals that make up the commissioning team to ensure that building HVAC systems perform as intended by the designer and building owner. Data was collected from commission professionals in construction, research and design fields. Qualitative data analysis yielded six primary themes that represent sub-themes that were repeatedly described as challenges, positive benefits or obstacles to progress. Thematic analysis of the primary themes peeked beneath the surface of the interview narratives to ask what is the structure that supports the major themes. Looking for broader implications and consequences, interpretation led to three proposed action topics. Recommendations are offered to improve commissioning practices by solving the implications of technology on human resources and developing partnerships with the industry that promote HVAC systems’ efficiency. Finally, a compilation of industry experts’ perspectives is laid out for re-aligning HVAC equipment, software, and controls technology to fully utilize the vast opportunities for utility savings, equipment longevity, and occupant comfort.

Keywords: HVAC, Commissioning, Cx, ASHRAE, Energy Efficiency, DDC

1. Introduction

Commissioning (Cx) is a plan (road map) consisting of steps and procedures to increase the reliability of any building system by designing, testing, and checking interfacing components to ensure the systems operates as intended by the designer and as requested by the owner. A commissioning process may be applied to any system -- electrical, mechanical or the building as a whole system. While it is most common for commissioning to be performed during new construction, it can be done at any point in a building’s life. Existing building commissioning (recommissioning) is a type of commissioning that is not done during new construction. Rather, recommissioning is done after the building or system has been functioning for years and seeks to ensure energy savings and operational improvements last over time. It may be initiated as part of a preventative maintenance plan or when the building function changes or as a diagnostic tool to identify causes of excessive energy usage or a need to investigate that minimum ventilation standards are met in a medical facility.

Retro-commissioning process involves investigating a building’s equipment and systems together after the facility HVAC equipment has been functional for months to years to understand and improve their operation. The facility owner/manager may have reported systemic operational problems since first occupation or issues that developed over the life of the building. A successful retro-commissioning means improved building performance with the addition of or fine-tuning of operations and maintenance procedures (O&M). Commissioning existing building systems has nearly unlimited potential for reducing the owner’s energy consumption and increasing equipment life because it is a systematic process for improving an existing building’s performance. The process will identify and allow implementation of relatively low-cost operational and maintenance improvements before an expensive loss of equipment occurs [1]. Ongoing commissioning combines continuous commissioning and monitoring-based commissioning (MBCx) and uses retro-commissioning techniques but adds the requirement for ongoing monitoring. Continuous and MBCx employ monitoring devices that collect energy use data based on equipment operation including hourly, daily, and seasonal energy use for the building. A departure from the energy use baseline then alerts the facility manager that the change might be an opportunity for improvements or repairs.

Monitoring-Based Commissioning or MBCX, is the newest technology for keeping buildings fit and equipment running as intended as an ongoing process. “MBCX leverages technology and innovative commissioning techniques to integrate energy management in a continuous fashion. Think of it as an ongoing process, wherein Monitor-Based Commissioning allows the commissioning agent to take a real-time look into building systems and operations, to fine-tune the system operations and identify areas that need improvement.” [2]. This research focuses on commissioning of Heating, Ventilating, Air Conditioning (HVAC) systems and explores HVAC commissioning as it has evolved with recent technological innovations in HVAC equipment as well as control/monitoring capability. The ability to remotely view and operate HVAC systems will be explored to establish the impact of HVAC Commissioning during initial construction and functional operation of buildings. Interactive access to HVAC equipment that allows visual real-time systems status, environmental setpoints, and trend reporting ability of remote creating lessons learned and recommendations from which corrective action and process revision can be implemented [3].

2. Literature Review

HVAC commissioning is a process that ensures that heating, ventilation, and air conditioning systems are designed, installed, and operated properly. It is a critical step in ensuring the energy efficiency, comfort, and durability of HVAC systems [4]. The commissioning process typically begins during the design phase of a project. The commissioning agent works with the architect, engineer, and contractor to develop a commissioning plan. The plan outlines the steps that will be taken to ensure that the HVAC system meets the owner's requirements. Commissioning of the HVAC systems often uncovers faulty equipment and mistakes that waste energy and adversely impact indoor air quality and comfort. Performance studies of schools’ HVAC systems found a short payback of 1–3-year payback from the investment of thorough commissioning of HVAC systems often due to correcting faults associated with the HVAC equipment and control [4].

Once the HVAC system is installed, the commissioning agent conducts a series of tests to verify that the system is operating as designed. These tests may include checking the system's energy efficiency, verifying that the system provides the desired level of comfort and ensuring that the system is operating safely. If any problems are found during the commissioning process, the commissioning agent works with the contractor to correct them. Once the system is operating properly, the commissioning agent prepares a commissioning report. The report documents the commissioning process and the results of the tests. HVAC commissioning can provide several benefits to building owners, including reduced energy costs, improved comfort, increased system reliability, extended system life and reduced maintenance costs [5]. The cost of HVAC commissioning varies depending on the size and complexity of the project. However, the benefits of commissioning can far outweigh the costs. HVAC commissioning is a wise investment that can help building owners save money, improve comfort, and extend the life of their HVAC systems [5].

In the connected information age, buildings are capable to be remotely monitored through connected devices and monitoring equipment [6]. With the rapid expansion of the Internet of Things (IoT), a plethora of new devices have been introduced, tested, and integrated into building and HVAC applications. These devices include low-cost and versatile sensors, smart thermostats, and occupancy sensors [6]. Studies have shown that use of connected buildings can potentially save building owners savings in energy costs [7]. Commissioning of these connected buildings requires a new forms of expertise to maximize the potential energy savings and performance efficiency [3]. This research explores the evolution of these new technologies and their impact on the commissioning process.

3. Research Methodology

HVAC commissioning experts and construction professionals were individually interviewed to capture the state of play, and the future of HVAC Commissioning by asking the following questions to reach the objective of the study:

- Gain an understanding of the challenges and benefits presented with innovative HVAC equipment commissioning processes to all the stakeholders in the construction lifecycle.
- Develop specific recommendations from research data to portray the present value and future benefit of online monitoring and control of Monitoring-Based Commissioning or MBCX.

The qualitative research method of conducting semi-structured interviews allows for discussion and follow up questions for a more thorough and nuanced understanding of the interviewees' experiences [8]. The insights developed from these interviews will be used to better understand HVAC commissioning as it relates to the design, construction, and occupancy of a building's life cycle. The literature review did not reveal information about the difficulties and high cost of the HVAC commissioning process. Nor did the literature speak to the common pitfall of HVAC commissioning delaying construction projects prior to building turnover. Interviews are important and vastly different than surveys. Surveys are predetermined questions that have minimal freedom and space for the surveyor to answer. While interviews usually have predetermined questions as a guide, the interviewer can change and adapt to the interviewee which allows them to continue with more detailed answers or to follow through on a topic that was not presented in the questions. The transcribed interviews were analyzed to find common themes that support valid recommendations for HVAC commissioning processes refinement.

3.1. Interview Questions

Interview questions were developed to gain a better understanding of the interviewees' experiences with HVAC Commissioning. Areas of special interest include determining the interviewees roles, experience levels and observations about the development of HVAC Commissioning practices from 1990's to present as well as their vision for the future. Each interviewee was asked to describe their experiences/roles with HVAC commissioning and number of years' experience in the industry so that a broad base of perspectives would be represented in the research data. After the introductions, the interviewer asked for general personal observations about the evolution of HVAC commissioning in their experience. The questions become more focused on the aims and objectives of the research topic with the follow-on questions about what primary technology advances in equipment or controls have expanded/affected HVAC Commissioning. Questions were formulated to find out if and why technology is helpful and probe into the challenges and potential solutions to technology problems encountered. The interviewer questioned how HVAC commissioning affects facility energy efficiency and whether there are negative impacts to owners. One of the final questions is intentionally open-ended inquiring as to the interviewee's opinion about the biggest challenge with HVAC commissioning. Lastly, participants were asked to share their thoughts about benefits and challenges of ongoing and recommissioning. Participants were selected based on their past and current roles in the HVAC Commissioning Industry and was invited by e-mail with a follow up phone call to describe the focus of the research questions. Survey participants will each be provided the same format with the same questions for consistency and transparency. This study interviewed 12 professionals to ensure adequate data collections can be used as this section for qualitative analysis.

4. Results

Content analysis and thematic analysis of the data was performed to understand the feedback from interview data. In this paper, only thematic analysis of the interview data that was performed to identify the main themes in the is presented, due to space restrictions. During the effort of reading, coding, and grouping the data, three unique themes emerged. These main themes and related issues are presented in a pictorial form and further discussed.

4.1. Build Work Force

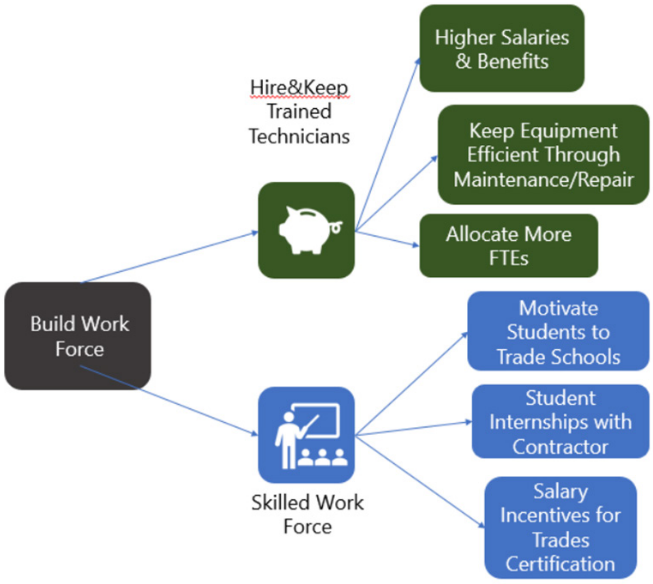

Figure 1 - Thematic Analysis – Build Work Force

A recurring pattern in the interviews described the lack of skilled work force within the members of the commissioning team. The participants responses included the roles of commissioning specialist, general contractor, mechanical and electrical subcontractors, controls technicians, facility managers and operators. The positions for these vital workers go unfilled for assorted reasons. The bottom line, though, is that people are not compelled to gain the skills for these trades nor pursue these types of vocations in sufficient numbers.

4.2. Prioritize through Education

Currently in the U.S., there is an emphasis to lower carbon emissions, conserving natural resources, and improved air quality by moving away from fossil fuel consumption. Considering that well-reported reality, one would surmise that most people in the U.S. possess a broad understanding of the role that HVAC systems play. However, the challenges of HVAC commissioning supported by the research data proves otherwise. Several participants observed that the HVAC commissioning is viewed as a misunderstood yet immense task that must be hurriedly accomplished before buildings can be occupied. The necessary end-of-project timing of the task does not motivate the contractor nor anyone on the commissioning team to be proactive about first rate installation and quick remedy of field problems. Even the owner is eager to cut corners during commissioning so they can get moved in. The education piece is supported by a respondent who stated, “*They're HVAC techs, and they have an aversion, to the control system, the electronic side. They want everything to be manual so they can go out there and flip a switch and turn a wrench and make it work. So, educating, teaching our technicians is still an issue*.”

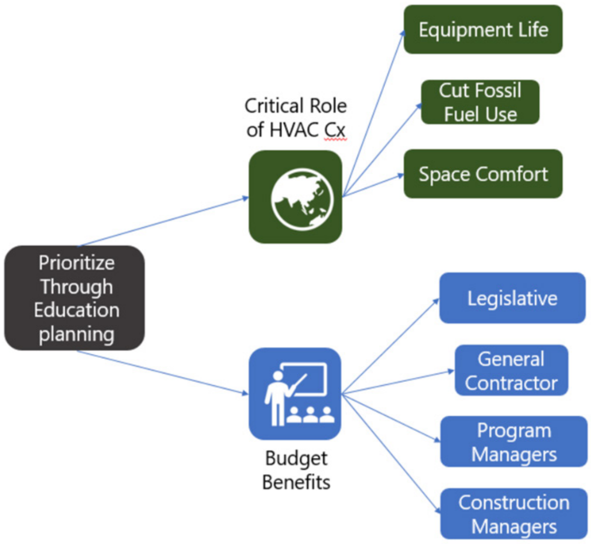

Figure 2 - Thematic Analysis – Prioritize through Education

4.3. Incentive Programs

A primary topic of interviewees was that federal or other government mandates for energy reduction focus on equipment energy ratings and annual energy reduction percentages for HVAC equipment. But the fact that facilities need to staff to check, adjust and repair the components that vibrate out of adjustment or fail because of wear is overlooked.

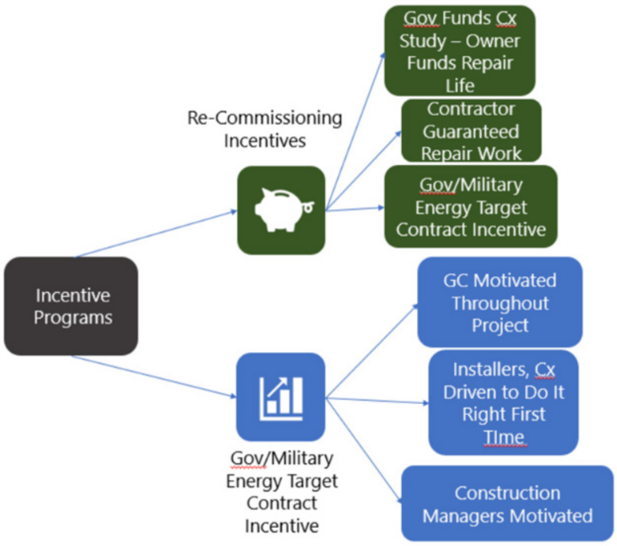

Figure 3 - Thematic Analysis – Incentive Programs

Commissioning is completed (poorly or well) and the assumption seems to be that the automation will take care of everything afterwards. Participants recommended that for buildings to work efficiently in terms of energy use of HVAC equipment, they must be regularly monitored and recommissioned. The general contractor can play a key role in ensuring that new buildings are properly commissioned by allocating sufficient time for the Cx process. It is well-known that profit is a motivating force for most people. If the energy mandates get the ball rolling toward energy efficiency, using creating monetary incentives that engage the commissioning process may keep it rolling along toward the goal. It was also recommended that incentives be included in the contracts to motivate all key participants in the construction process to get it right the first time.

5. Conclusions

Technical experts, construction managers, and owners provided insights into pitfalls in schedule progress during commissioning and noted that the inherent focus on moving to the next project encourages parties to forego important last steps in the process such as second season testing and facility occupancy scheduling. Valuable lessons were shared and recommendations with high potential for success were brought forward in the interview dialogue. The participants responses offered a comparison of pros and cons about the merit and relevancy of ongoing and re-commissioning. The review of the history and progress of HVAC Commissioning verified that technology advances such as direct digital controls, Wi-Fi-enabled remote monitoring and software that diagnoses mechanical system problems has a significant effect on building systems' energy efficiency. Literature review presented the previous and current state of HVAC Commissioning to allow a comparison of differences, benefits, and disadvantages. The interview dialogue with industry installers, contractors, owners, and designers provided an understanding of the reality of the challenges with and potential of innovative HVAC equipment, controls, and in the facility lifecycle.

By objective examination of common themes and parallel perspectives, the research presents an image of the HVAC commissioning industry highly impacted by technology but struggling to overcome a critical gap of people with the skills and incentive to meet the intent of the commissioning process. The impact of technology on HVAC Commissioning is direct and simple if one merely looks at direct digital controls and computer advances. Participants widely agreed that the onset of digital components and electronic communication was an incredible boost to the ability to commission HVAC systems. However, complexity and human factors are variables that complicate full utilization. Technology is not the problem, but its implications must be considered. Some salient recommendations of this research include the following:

- Develop programs to encourage students to learn a trade that supports HVAC Commissioning.
- Develop creative ways to incentivize high quality HVAC installation, Commissioning to ensure facility utility savings are a reality.
- Establish an educational campaign focused on increasing awareness about the pivotal role of HVAC Commissioning in advancing the goal of enhancing HVAC system efficiency by minimizing energy use.

References

[1] K. Johnson, "What are the different types of building commissioning?," *kW Engineering*, Dec. 13, 2019. https://kw-engineering.com/different-types-building-commissioning/ (accessed May 14, 2023).
[2] admin, "What is Commissioning?," *Jordan & Skala Engineers*, Jul. 23, 2020. https://www.jordanskala.com/what-is-commissioning/ (accessed May 14, 2023).
[3] L. S. Brambley Gang Wang, Michael, "Building Automation System Embedded HVAC System Energy Performance Degradation Detector*," in *Automated Diagnostics and Analytics for Buildings*, River Publishers, 2014.
[4] M. Virta, *HVAC Commissioning Guidebook*. CRC Press, 2021.
[5] R. Ellis, "Tab is a Prerequisite for Functional HVAC System Performance | 2020-01-09 | Engineered Systems Magazine." https://www.esmagazine.com/articles/100083-tab-is-a-prerequisite-for-functional-hvac-system-performance (accessed May 14, 2023).
[6] Y. Bae *et al.*, "Sensor impacts on building and HVAC controls: A critical review for building energy performance," *Advances in Applied Energy*, vol. 4, p. 100068, Nov. 2021, doi: 10.1016/j.adapen.2021.100068.
[7] D.-B. Kim, D. D. Kim, and T. Kim, "Energy performance assessment of HVAC commissioning using long-term monitoring data: A case study of the newly built office building in South Korea," *Energy and Buildings*, vol. 204, p. 109465, Dec. 2019, doi: 10.1016/j.enbuild.2019.109465.
[8] E. Ahlin, *Semi-Structured Interviews With Expert Practitioners: Their Validity and Significant Contribution to Translational Research*. 1 Oliver's Yard, 55 City Road, London EC1Y 1SP United Kingdom: SAGE Publications Ltd, 2019. doi: 10.4135/9781526466037.

EXPLORING THE ROLE OF INDUSTRY 4.0 IN THE BUILDING INDUSTRY: A CASE STUDY OF EMERGING BUSINESS MODELS IN THE AUSTRALIAN CONSTRUCTION ECOSYSTEM

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Abstract

As the building industry is a significant contributor to Australia's economy, understanding the impact of Industry 4.0 on this sector is crucial for its continued growth and competitiveness. This creates a need to explore the interdependencies between the implementation of an industrial and digitally enabled building industry and business model and value chain innovation to shape a digitally mediated platform ecosystem configuration. As the building industry faces challenges in adopting manufacturing techniques and technologies, the paper examines significant yet understudied implications of Industry 4.0 along industrial value chains. This study aims to understand how the building industry in Australia can adapt to the shift towards industrialised-digitalisation by exploring the opportunities for innovation in business models and value chains. The research approach will draw on a literature review, and a series of workshops in four Australian cities to understand perspectives determining business model innovation. Examining integration, servitization, and expertization the paper illuminates the impact of digital connectivity, information exchange, and design value on the industry. The paper's framework focuses on assessing dynamic capabilities (sensing, seizing, and reconfiguring) and the ecosystem lifecycle (birth, expansion, leadership, self-renewal) to comprehend business model innovation in the Australian construction ecosystem. It also uncovers how diverse stakeholders, including developers, contractors, consultants, supply chain actors, and digital platform owners, create value and progress through these phases. Identifying prospects in offsite manufacturing, standardization, technological advances, and value chain integration allows developers, clients, and contractors to enhance efficiency and results. Consultants can utilize their design value and project management know-how to promote cooperation among stakeholders. Additionally, digital platform proprietors can access multi-sided marketplaces for direct communication and efficient procedures. Ultimately, implementing these insights assists industry participants in adapting to changing market dynamics, encouraging innovation, and bolstering the competitiveness of the Australian construction industry.

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Keywords: Industry 4.0, value chains, platform, ecosystems, business model innovation

1.0 Introduction

Industry 4.0 is catalyzing a gradual change in the construction industry's paradigms. Most existing research in the built environment focuses on the remarkable technological capabilities of Industry 4.0, with minimal attention given to its effects on the construction business model. However, responsible innovation takes place at the level of the business model itself reconceptualizing the fundamental role of business in society [1]. Since the advent of Industry 4.0, construction firms are experiencing significant changes in their existing business models; Industry 4.0 technologies can create new value propositions, expand customer segments, influence channels and modify key activities through automation and data-driven operations [2]. Initial studies discussing business models in construction-related literature do not align with the definition of a business model as "a representation of an organization's value logic"; Instead, these studies treat business models as a way to justify costs, essentially discussing to them as commercial models [3, 4]. In this regard, Pekuri, et al. [5] argued that construction managers had trouble articulating their company's business model and value-creation logic, indicating a limited understanding of customer values. Boldly, the study suggested that this could be a primary cause of the ongoing customer dissatisfaction prevalent in the industry. Although business model innovation has been recognized as a "theory of business" since Drucker [6], it has only recently captured the interest of researchers in the built environment primarily due to the emergence of two main streams of research, industrialised house building business models [7, 8] and circular business models [9, 10] because both of these approaches to construction created added value in terms of efficiency, sustainability, continuous improvement, customer-centricity to name a few that could be monetized. Analysing construction firms using the lens of a business model can help address two of construction’s eternal problems; firstly, develop an increased understanding of customer values [11] and secondly, look at a firm’s value creation and value capturing interlinkages with a holistic view and not stagewise (design, construction, operation) or project-wise (one project to another) [7].

In a very recent study by Criado-Perez, et al. [12], the authors investigated the prevailing issues in the digital transformation of the Australian construction sector. While the apparent cause identified were skill deficit, resistance to change, insufficient investment in digital infrastructure and regulatory challenges, Criado-Perez, et al. [12] stressed on an underlying cause; Construction firms are engaging in sporadic digital transformation efforts that primarily focus on technology, without giving due consideration to the underlying business model; as a result, these initiatives often face difficulties when it comes to scaling up. The authors They recommend embedding business model thinking in the industry which involves an understanding of how to proactively change an existing business model. Given the above, this paper is an attempt to answer the question, ‘*How will business models transform in the Australian construction ecosystem in Industry 4.0?’.* Therefore, this study aims to understand how the building industry in Australia can adapt to the shift towards industrialized-digitalization by exploring the opportunities for innovation in business models and value chains. The paper is structured as follows: Section 2 presents a critical literature review on Industry 4.0 and value chains, industrialized-digitalized business models and how to create, offer and capture value in Industry 4.0. Section 3 presents the research approach taken in this paper. Section 4 presents the findings followed by a discussion of the findings in Section 5. Section 6 concludes the paper and presents future research directions. The paper is a result of an ongoing research initiative, findings will be further developed as the project reaches completion.

2.0 Literature Review

2.1 Industry 4.0 and Value Chains

Industry 4.0 necessitates a re-evaluation of traditional business strategies by focusing on fostering collaborative ecosystems enabled by digital capabilities [13]. ‘Virtual value chains’ characterized by digital connectivity, information sharing, and real-time data exchange emerged in Industry 4.0 to facilitate better decision making [14]. Nottbrock, et al. [15] stated that Industry 4.0 innovations are shifting value chain structures from linear, hierarchical models towards more decentralized, networked configurations enabling greater flexibility, collaboration, and co-creation among various stakeholders. Dzwigol, et al. [16] also highlighted the importance of collaboration and ecosystem-based thinking in the Industry 4.0 era where organizations need to establish partnerships with various stakeholders, including suppliers, customers, research institutions, and competitors, to share knowledge, resources, and capabilities in a rapidly changing environment. Taking the case of the manufacturing sector, Culot, et al. [17] observed that Industry 4.0 technologies, such as IoT, AI, and big data analytics, are enabling greater integration within manufacturing value chains facilitating real-time data exchange, improved communication, and enhanced collaboration among value chain actors. The study adds that Industry 4.0 technologies also impact the scalability of manufacturing value chains; advanced manufacturing techniques, such as additive manufacturing and automation, allow firms to achieve greater flexibility and responsiveness to market changes, enabling them to scale production more effectively. Similar observations have been reported from the textile industry. Chen [18] stated that cooperation can facilitate knowledge sharing, technology transfer, and joint innovation, which can further boost value creation in large textile firms as well as SMEs. Thus, there is consensus in the literature that Industry 4.0 is driving the development of new business models that rely on collaboration, data-driven decision-making, and customer-centricity [14, 19, 20]. Consequently, it has been found that assessing the integration of digital technologies and innovative business models at each stage of the value chain can help organizations better understand the overall effects of Industry 4.0 on their operations [21].

2.2 Industrialized - Digitalized Business Models

Industry 4.0. business models are impacted by the twin currents of industrialisation and digitalisation. Weking, et al. [22] investigated 32 case studies of Industry 4.0 business model innovation and identified that *integration, servitization and expertization* are the three super patterns of business model innovation in Industry 4.0; integration attempts to integrate parts of the supply chain through new processes whereas new combined products and services are the basis for servitization. Expertization is a hybrid approach that utilizes product and process focussed business models including consulting services and multi-sided platforms. Mass customization is a form of integration, life-long partnerships a form of servitization and product or process-related platformisation are forms of expertization. Similar findings were reflected in Ibarra, et al. [23] where the authors identified three complementary approaches to business model innovation in Industry 4.0; service orientation, networked ecosystems and customer orientation. They can be described as specific product-service bundles as a solution for the customer where suppliers, customers and other partners become part of a networked ecosystem; often new actors arise and the roles of existing actors change. Customer orientation requires firms to develop new capabilities in learning more about their customers and their value creation process utilising digital means. Digital platforms serve as catalysts for inter-organizational cooperation and enable businesses to co-create value. Veile, et al. [24] investigated industrialised-digitalised business models by critically reviewing 11 cases to understand how digital platforms change industrial firm's business model and inter-company relationships. The study highlighted key aspects of such business models; *customer relationships* - customer integration from silos to cooperation, new forms of buyer-supplier relationships; *key partners* – ecosystem partners with higher levels of trust among partners, new ways of digital communication and higher communication frequency; *key activities* – pre-phase platform creation, recurring tasks ecosystem development; *key resources* – technological and digital along with human resources and knowledge; *value propositions* – improved value offers (processes), extended value offers (services), value through data and digitalisation; *channels* – direct channels through the platform and indirect channels through the ecosystem. Thus, it is evident that digital platforms serve as catalysts for inter-organizational cooperation and enable industrial firms to co-create value [25].

2.3 Creating, Offering and Capturing Value in Industry 4.0

Exemplars of how value is created, offered and captured in industrialised-digitalised business models were demonstrated in Müller and Buliga [26]; real-time sensor data, simulation and data analytics, condition monitoring, predictive maintenance and preventive maintenance are exemplars of value creation; reducing time customers spend designing prototypes, reducing customer's unexpected downtimes, optimizing energy consumption in the production line are exemplars of value offer and licensing, subscription, pay-per-use, pay-per-feature, pay for guaranteed results etc. are exemplars of value capture. Similar findings are reflected in an extended work by Müller, et al. [27] where they stated that value is created at manufacturing sites through high-grade digitalization of manufacturing data which allows demand optimization, failure reduction, and productivity increases (value offer). Ibarra, et al. [23] propose a four-step framework to shift from traditional business models to new business models and illustrate how value can be created, delivered (offered) and captured at each step. The four steps proposed in the study are internal and external process optimisation, customer interface improvement, new ecosystems and value networks and new business models (smart product and services); they demonstrate a shift from incremental innovation to radical innovation. For example, at the process optimization stage, value is created through more efficient production, logistics, quality control and more transparent management (data-driven); value is delivered through more flexible offers including customization and value is captured through cost optimization due to more efficient processes and use of resources. On the other end of the spectrum, at the new business model stage value is delivered through smart products, innovation in associated services (such as predictive maintenance), co-creation that includes customers in the value creation process and direct relationships between the firm and the customers. This requires value creation through new physical, human and intellectual resources and allows for value capture through new revenue streams such as dynamic pricing, pay-per-use etc. The different mechanisms for value creation, offer and capture in Industry 4.0 business models were assimilated from literature and presented in Table 1.

Table 1. Value creation, offer and capture in Industry 4.0 business models [22, 23, 27]

Value creation	Value offer	Value capture
Customization - Mass production, mass customisation, mass individualisation *Role of a value chain firm* – integrator, service and support, intermediary *Factory* – mega factory, micro factory *Production paradigm* – pull / on-demand, push & pull *Partners* – higher intercompany connectivity, co-design of value offers, joint data analysis, higher information transparency *Information exchange* – real time information about production, inventories, sales, availability of personnel, etc.	*Products* – Physical only, physically, digitally charged, digital only *Service* – Repair & maintenance, monitoring and predictive maintenance, production, technology, advice & consulting, digitalization services, data analytics services, virtual product development	*Market* – B2B only, B2C only, B2B & B2C, multi-sided market *Segmentation* – Based on customer knowledge and data analysis *Customer interaction* – hybrid (direct and intermediary), direct selling leading to long-term relationships *Revenue model* – sales, revenue sharing, freemium, rent/lease, subscription, pay-per-use, pay-per-feature *Continuity of revenue* – once, mixed, continuous *Sales model* – ownership / service delivery, use / availability, result *Payment methods* – Digital accounting and automated invoices, increased payment reliability *Cost* – Potential for cost reduction for all stakeholders due to most efficient processes and information sharing

The following section will elaborate on the research approach taken in this paper.

3.0 Research Approach

Workshops as a research methodology have been used in prior research to identify, articulate and explore problems in areas where there is a lack of common language to produce reliable and valid data about the domain being investigated [28]. The research approach in this paper follows the four-step framework proposed by Storvang, et al. [29] to use workshops in business research. The four steps as illustrated in Fig. 1., comprise the diagnosis, planning, facilitating and analysis phases. The diagnosis phase involves understanding the system within which the research problem resides which was accomplished through a critical review of literature on Industry 4.0 value chains and business models in this paper. The planning phase involves selecting the participants, venue and developing the content for the facilitated workshops. In this phase, the social process of what the participants will be doing in the workshop and what would they get out of it is defined along with technical considerations such as context, time and place. In this paper, workshops were scheduled to be conducted in four Australian cities of Adelaide, Melbourne, Sydney and Brisbane; of which the workshops in Adelaide and Melbourne have already been conducted and the ones in Sydney and Brisbane are scheduled for the month of May 2023.The participants were invited from all stakeholder groups in the construction value chain including architects, engineers, consultants, contractors, government bodies, digital platform providers and representatives from client bodies. The total number of participants in the Adelaide and Melbourne workshops amounted to 60. The facilitated workshops ran for an entire day with the morning sessions dedicated to presenting the literature findings and educating the participants about Industry 4.0, the shift in value chains from linear, hierarchical models towards more decentralized, networked configurations or ecosystems and the various mechanisms of value creation, offer and capture in Industry 4.0 business models. The afternoon sessions were utilised to facilitate discussions on the opportunities and challenges of the new ecosystem in the context of the Australian construction sector. Mentimeter, which is considered as an effective tool to engage a cohort of participants [30, 31] was used for real-time data collection on the opportunities and challenges. The final phase is the analysis phase where the data collected from the workshops were evaluated and related back to the original research question, '*how will business models transform in the Australian construction ecosystem in Industry 4.0*?' The four steps are iterative given there are four facilitated workshops, with minor fine-tuning after each workshop to evolve from pre-understanding to understanding to a new level of understanding and so on [29]. The following section presents the findings of the paper.

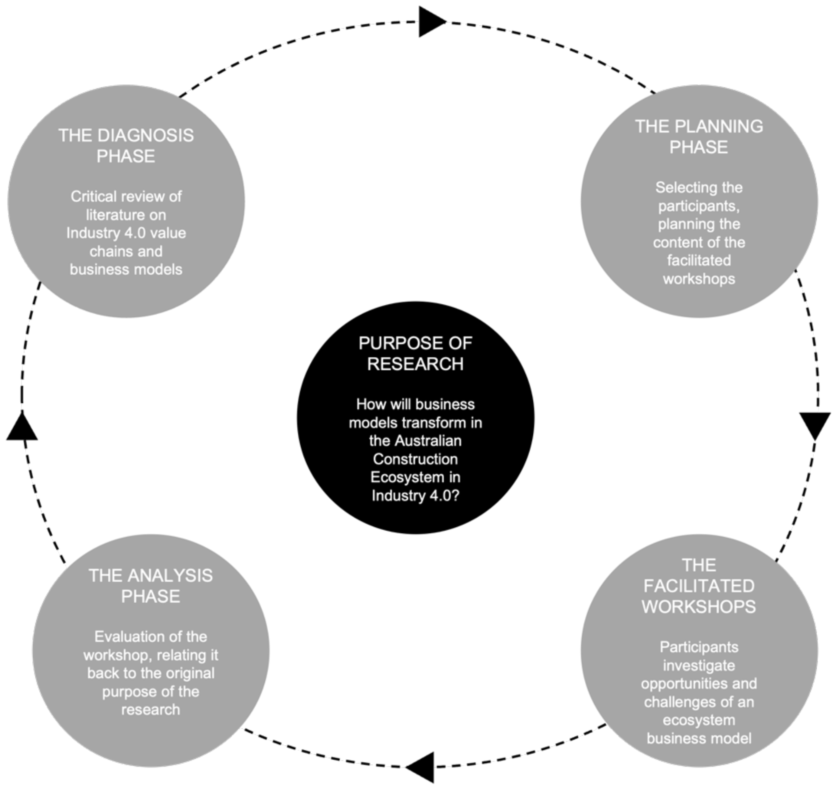

Fig. 1. Research Approach

4.0 Findings and Discussion

4.1 Digitally mediated ecosystems business models

The Australian construction ecosystem has produced exemplars of all three archetypes of Industry 4.0 business model innovation identified from the literature; integration, servitization and expertization [22]. One of the main benefits of the ecosystem business model that the workshop participants consented to was the opportunity to move value adding activities upstream; which is an exemplar of integration. Some of the Mentimeter outputs have been quoted as is; *"I am a prefab manufacturer, and I can be involved at a design level as early as possible in a project lifecycle to provide constructability input…. I am a modular builder and I can assemble a complete value chain and bid for a complete package rather than small elements…."* Complementing what the literature says, the participants believed that such supply chain integration is enabled through digital connectivity, information sharing, and real-time data exchange [14]. New combined products and services is the basis of servitization which was also evident among the workshop responses. *"I am a steel manufacturer and supplier, and I can bundle value-added elements for example, I can embed digital services for condition monitoring…."* As seen in Müller and Buliga [26], real-time sensor data, simulation and data analytics, condition monitoring, predictive maintenance and preventive maintenance exemplify value creation in industrialised-digitalised business models. Exemplars of expertization represents a blended strategy that employs both product-centric and process-centric business models, incorporating consultancy services and multi-sided platforms [22]; the participants belonging to the stakeholder group 'architects' aligned most with the expertization business model. *"I am an architect and I can pivot to the design of systems and not buildings using parametric and generative design tools; I can then directly engage with the supply chain during design instead of traditional linear additive procurement. I can design smarter and cleaner as part of an ecosystem led by multiple agendas…."* This supports the fact that design value holds the key to accessing untapped markets, ensuring responsible design and enhancing cost-effectiveness; This value not only brings about tangible business advantages, but also enriches the wider social, cultural, and economic aspects of a building [32]. The workshop participants repeatedly raised the point about directly engaging with the supply chain. This is also evident in some real industry cases where multi-sided platforms are being utilised for direct buying and selling. A start-up that originated in Sydney, Australia called ptblink, offers a digital platform that enables the parametric design of multi-storey buildings as a kit of configurable parts and then provides a marketplace for direct dealing between buyers and sellers. They consider themselves a software development company now, but they have evolved from a construction background in the 1990s thereby representing 'expertization'.

4.2 Dynamic Capabilities

The workshop inputs were further analysed by mapping them to existing frameworks in the literature to understand the current status of business model innovation in the Australian construction ecosystem. Dynamic capabilities empower business models, as organizations with such abilities can swiftly test and fine-tune novel business models [33]; dynamic capabilities include the evaluation of technological opportunities and threats in relationship to customer needs (sensing), mobilization of resources to address those needs and capture value from doing so (seizing), and continued renewal (reconfiguring) [34]. A set of dynamic capabilities are required for each stage of the ecosystem lifecycle [35]. The lifecycle of an ecosystem commences when a value proposition is devised (birth), continues with scale and refinement (expansion), becomes stronger by keeping customers and partners engaged (leadership) and finally reconfigures with new ideas (self-renewal) [36]. Industry stakeholders are sensing business model innovation opportunities through shifting of on-site construction to offsite manufacturing, standardising components into a predefined platform, systematically using building projects to develop the platform and aiming for improved efficiency through technology innovation; as they integrate value-chains by building specifications that conform to both the platform and client requirements through standardization of processes and long-term agreements or relationships, they are moving into the seizing stage; and they can reconfigure through cross-industry collaboration and research, routinized learning and cyclic business streams [37, 38]. From the responses, developers, clients and contractors are actively sensing opportunities and moving into the expansion stage of the ecosystem lifecycle. Consultants have capability within their businesses to guide this ecosystem; both in terms of 'design value' and 'project management'. Quoting a project management consultant among the participants; *"I am a project management consultant and I can curate a team of likeminded businesses/producers on a project. I can bring the client, design team, builders and subcontractors together to work towards the best outcomes for all involved…."* As noted earlier in the discussion, associated supply chain actors such as prefab manufacturers, material manufacturers and suppliers and modular builders are already seizing business model innovation opportunities through value chain integrations and servitization business models. Slightly ahead in the trajectory are some of the digital platform owners that are already reconfiguring through multi-sided marketplaces. Fig. 2 illustrates the current status of business model innovation in the Australian construction ecosystem.

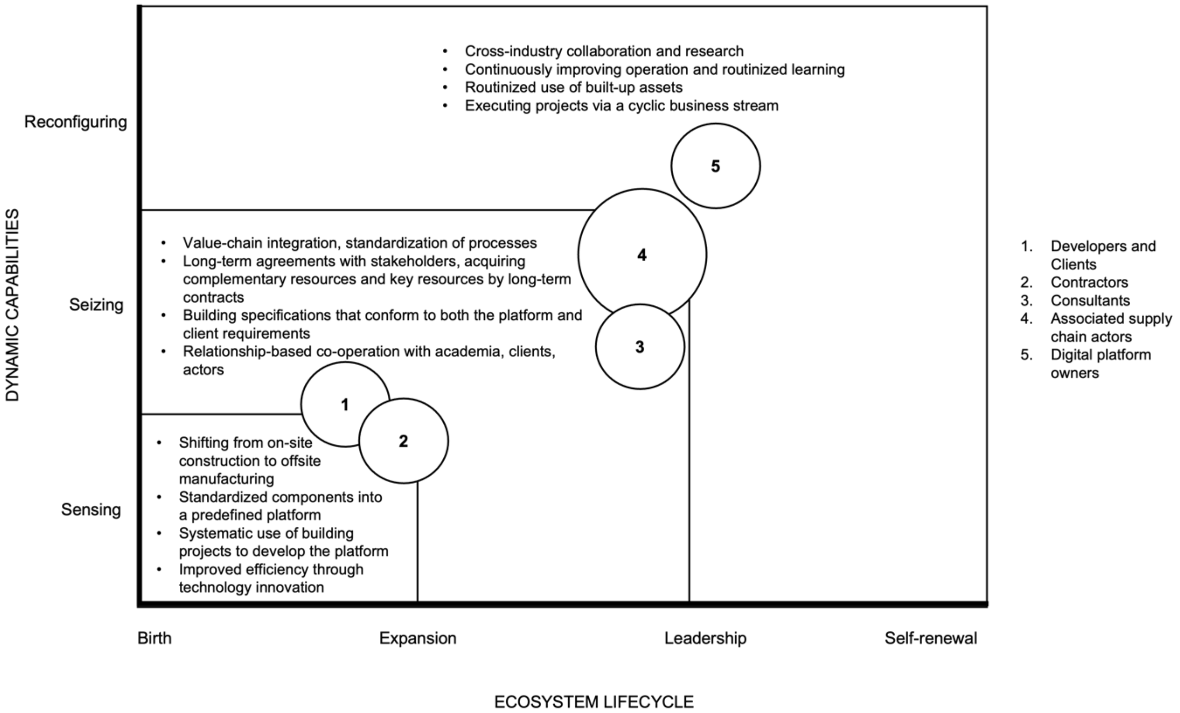

Fig. 2. Business Model Innovation in the Australian construction ecosystem

4.3 Challenges

The workshop also discussed the challenges towards adoption of an ecosystem business model. The primary concern among supply chain stakeholder groups was interoperability in case the ecosystem business model encompassed a product platform. According to platform theory, product platforms should have defined interfaces which can be made available to the designers and suppliers of peripheral or complementary products. This should enable the product platform to be reliably integrated with other parts of a building without being wholly dependent on the platform provider [39]. However, the participants expressed concern on whether the products they offer will be compatible with the platform. *"I am a bathpod manufacturer and I don't know if my products will be compatible with the platform…."* Ecosystem business models yield advantages when shared resources are utilized at scale; Although this presents opportunities for enhanced efficiency and cost savings, it may also raise issues related to intellectual property, risk management, and liabilities [39]. This was a major concern among the workshop participants too. *"I am a contractor and now I have more data, risk and exchanges occurring across the ecosystem…."* The workshop participants were of the view that cultural barriers will perhaps be the biggest roadblock towards implementing such an ecosystem business model. Collaborative exchanges and early involvement are difficult in an industry that is historically categorised as fragmented with adversarial relationships among its stakeholder groups [7]. There was consensus among the participants that traditional expectations of return on investment and short-term thinking were still prevalent in the industry. Owning and participating (ecosystem business model) can provide better returns over a longer term; however, a collaborative commons approach is yet to take over from pure capitalism in the industry. *"I am a modular builder and it is a challenge to convince all stakeholders to collaborate and initiate a cultural shift in the industry…." "I am a modular builder and it is a challenge to convince the client to adopt a new business model…."* Embracing an ecosystem approach as a novel business model, might necessitate modifications in the contractual arrangements among organizations. Ensuring well-defined relationships, aligned interests, and suitably distributed risks within the ecosystem will be crucial [39]. The participants concluded that even though stakeholder groups have the ability to involve from the moment of inception to create better value for the client, the current rigid procurement model and contractual arrangements do not allow for such innovation to occur. The final challenge identified was skill deficit. "I am a contractor and my challenging is keeping up with the changing perceptions within the business and building the skills to deliver prefab projects…." To achieve the benefits of an ecosystem business model it requires the development of new skills, new ways of works and collaboration, both across and within organisations in the value chain [39]. It is a subject of further research leading to policy decisions.

5.0 Conclusions and Future Research

The theoretical contribution of this paper lies in illustrating the application and manifestation of Industry 4.0 business model innovation within the Australian construction ecosystem. By exploring integration, servitization, and expertization, it sheds light on the role of digital connectivity, information sharing, and design value in shaping the industry. The framework proposed in the paper centres on the analysis of dynamic capabilities (sensing, seizing, and reconfiguring) and the ecosystem lifecycle (birth, expansion, leadership, self-renewal) to understand business model innovation in the Australian construction ecosystem. The paper reveals how various stakeholders, such as developers, contractors, consultants, associated supply chain actors and digital platform owners are embracing opportunities and transitioning through these stages. By examining their roles and progress, the paper offers insights into the current state and future direction of business model innovation in the Australian construction sector.

The practical implications of the paper suggest that stakeholders in the Australian construction ecosystem can benefit from understanding and embracing dynamic capabilities and the ecosystem lifecycle stages to drive business model innovation. By recognizing opportunities for offsite manufacturing, standardization, technology innovation, and value chain integration, developers, clients, and contractors can improve efficiency and project outcomes. Consultants can leverage their expertise in design value and project management to facilitate collaboration among all parties. Furthermore, digital platform owners can tap into multi-sided marketplaces to enable direct interactions and streamlined processes. Overall, applying these insights can help industry players adapt to the evolving market conditions, foster innovation, and enhance the competitiveness of the Australian construction sector.

The challenges associated with the ecosystem business model identified in this paper provides a clear direction for future research. Future research needs to (a) investigate strategies to ensure compatibility and seamless integration between product platforms and peripheral or complementary products to address concerns raised by industry stakeholders (b) examine the challenges and potential solutions related to shared resources, intellectual property rights, and risk distribution in an ecosystem business model (c) explore the factors that hinder collaboration and early involvement in the construction industry, and identify ways to foster a shift towards a more collaborative commons approach (d) assess the impact of novel business models on contractual arrangements, and develop frameworks for well-defined relationships, aligned interests, and suitable risk distribution within the ecosystem (e) analyze the skill gaps and challenges faced by industry professionals in adapting to ecosystem business models, and propose strategies for skill development and capacity building within the sector and (f) examine the potential policy decisions that can support the adoption of ecosystem business models in the construction industry.

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References

[1] A. Hope and R. Moehler, "Responsible Business Model Innovation: Reconceptualising the role of business in society," in *EURAM 2015: 15th Annual Conference of the European Academy of Management*, Warsaw, Poland, 17th - 20th June 2015.

[2] P. Das, S. Perera, S. Senaratne, and R. Osei-Kyei, "Developing a Construction Business Model Transformation Canvas," *Engineering, Construction and Architectural Management,* vol. 28, no. 5, pp. 1423-1439, 2020, doi: https://doi.org/10.1108/ECAM-09-2020-0712.

[3] B. Duyshart, D. Walker, S. Mohamed, and K. Hampson, "An example of developing a business model for information and communication technologies (ICT) adoption on construction projects–the National Museum of Australia project," *Engineering, Construction and Architectural Management,* vol. 10, no. 3, pp. 179-192, 2003, doi: https://doi.org/10.1108/09699980310478430.

[4] G. Seaden, M. Guolla, J. Doutriaux, and J. Nash, "Strategic decisions and innovation in construction firms," *Construction Management and Economics,* vol. 21, no. 6, pp. 603-612, 2003, doi: https://doi.org/10.1080/0144619032000134138.

[5] A. Pekuri, L. Pekuri, and H. Haapasalo, "The role of business models in Finnish construction companies," *Australasian Journal of Construction Economics and Building,* vol. 13, no. 3, pp. 13-23, 2013, doi: https://search.informit.org/doi/abs/10.3316/INFORMIT.604698372257240.

[6] P. F. Drucker, *Managing in Turbulent Times*. New York: Harper & Row, 1980.

[7] D. M. Hall, J. Lessing, and J. Whyte, "New Business Models for Industrialized Construction," in *Industry 4.0 for the Built Environment*, vol. 20, M. Bolpagni, R. Gavina, and D. Ribeiro Eds.: Springer, 2022, pp. 297-314.

[8] J. Lessing and S. Brege, "Industrialized building companies' business models: Multiple case study of Swedish and North American companies," *Journal of Construction Engineering and Management,* vol. 144, no. 2, p. 05017019, 2018, doi: https://doi.org/10.1061/(ASCE)CO.1943-7862.0001368.

[9] M. R. Munaro, M. d. C. D. Freitas, S. F. Tavares, and L. Bragança, "Circular business models: Current state and framework to achieve sustainable buildings," *Journal of Construction Engineering and Management,* vol. 147, no. 12, p. 04021164, 2021, doi: https://doi.org/10.1061/(ASCE)CO.1943-7862.0002184.

[10] X. Zhao, B.-G. Hwang, and Q. Lu, "Typology of Business Model Innovations for Delivering Zero Carbon Buildings," *Journal of Cleaner Production,* vol. 196, pp. 1213-1226, 2018, doi: https://doi.org/10.1016/j.jclepro.2018.06.018.

[11] J. Lessing and S. Brege, "Business models for product-oriented house-building companies – experience from two Swedish case studies," *Construction Innovation,* vol. 15, no. 4, pp. 449-472, 2015, doi: https://doi.org/10.1108/CI-02-2015-0009.

[12] C. Criado-Perez *et al.*, "Digital Transformation in the Australian AEC Industry: Prevailing Issues and Prospective Leadership Thinking," *Journal of Construction Engineering and Management,* vol. 148, no. 1, 2022, doi: https://doi.org/10.1061/(ASCE)CO.1943-7862.0002214.

[13] R. Strange and A. Zucchella, "Industry 4.0, global value chains and international business," *Multinational Business Review,* vol. 25, no. 3, pp. 174-184, 2017, doi: https://doi.org/10.1108/MBR-05-2017-0028.

[14] B. Semolic and P. Steyn, "Industry 4.0 Virtual Value Chains and Collaborative Projects," *PM World Journal,* vol. 6, no. 9, pp. 100-123, 2017, doi: https://www.cranefield.ac.za/wp-content/uploads/2019/07/PMWJ-Vol-VI-Issue-IX-Sept-2017-Industry-4.0-Virtual-Value-Chains-and-Colalborative-Projects-Semolic-and-Steyn.pdf.

[15] C. Nottbrock, A. Van Looy, and S. De Haes, "Impact of digital Industry 4.0 innovations on interorganizational value chains: a systematic literature review," *Business Process Management Journal,* vol. 29, no. 1, pp. 43-76, 2023, doi: https://doi.org/10.1108/BPMJ-06-2022-0259.

[16] H. Dzwigol, M. Dzwigol-Barosz, and A. Kwilinski, "Formation of global competitive enterprise environment based on industry 4.0 concept," *International Journal of Entrepreneurship,* vol. 24, no. 1, pp. 1-5, 2020, doi: https://www.proquest.com/openview/b2c4ea1b3494aa8a22c69a79da400c56/1?pq-origsite=gscholar&cbl=29727.

[17] G. Culot, G. Orzes, and M. Sartor, "Integration and scale in the context of Industry 4.0: the evolving shapes of manufacturing value chains," *IEEE Engineering Management Review,* vol. 47, no. 1, pp. 45-51, 2019, doi: https://doi.org/10.1109/EMR.2019.2900652.

[18] C.-L. Chen, "Value creation by SMEs participating in global value chains under industry 4.0 trend: Case study of textile industry in Taiwan," *Journal of Global Information Technology Management,* vol. 22, no. 2, pp. 120-145, 2019, doi: https://doi.org/10.1080/1097198X.2019.1603512.

[19] M.-C. Schmidt, J. W. Veile, J. M. Mueller, and K.-I. Voigt, "Ecosystems 4.0: Redesigning global value chains," *The International Journal of Logistics Management,* vol. 32, no. 4, pp. 1124-1149, 2021, doi: https://doi.org/10.1108/IJLM-03-2020-0145.

[20] Y. Yu, J. Z. Zhang, Y. Cao, and Y. Kazancoglu, "Intelligent transformation of the manufacturing industry for Industry 4.0: Seizing financial benefits from supply chain relationship capital through enterprise green management," *Technological Forecasting and Social Change,* vol. 172, p. 120999, 2021, doi: https://doi.org/10.1016/j.techfore.2021.120999.

[21] I. Castelo-Branco, T. Oliveira, P. Simões-Coelho, J. Portugal, and I. Filipe, "Measuring the fourth industrial revolution through the Industry 4.0 lens: The relevance of resources, capabilities and the value

chain," *Computers in Industry,* vol. 138, p. 103639, 2022, doi: https://doi.org/10.1016/j.compind.2022.103639.

[22] J. Weking, M. Stöcker, M. Kowalkiewicz, M. Böhm, and H. Krcmar, "Leveraging industry 4.0–A business model pattern framework," *International Journal of Production Economics,* vol. 225, p. 107588, 2020, doi: https://doi.org/10.1016/j.ijpe.2019.107588.

[23] D. Ibarra, J. Ganzarain, and J. I. Igartua, "Business model innovation through Industry 4.0: A review," *Procedia manufacturing,* vol. 22, pp. 4-10, 2018, doi: https://doi.org/10.1016/j.promfg.2018.03.002.

[24] J. W. Veile, M.-C. Schmidt, and K.-I. Voigt, "Toward a new era of cooperation: How industrial digital platforms transform business models in Industry 4.0," *Journal of Business Research,* vol. 143, pp. 387-405, 2022, doi: https://doi.org/10.1016/j.jbusres.2021.11.062.

[25] S. King and S. S. Grobbelaar, "Industry 4.0 and business model innovation: a scoping review," in *2020 IEEE International Conference on Engineering, Technology and Innovation (ICE/ITMC)*, 2020: IEEE, pp. 1-8, doi: https://doi.org/10.1109/ICE/ITMC49519.2020.9198424.

[26] J. Müller and O. Buliga, "Archetypes for data-driven business models for manufacturing companies in industry 4.0," in *International Conference on Information Systems 2019 Special Interest Group on Big Data Proceedings*, 2019, doi: https://aisel.aisnet.org/sigbd2019/2.

[27] J. M. Müller, O. Buliga, and K.-I. Voigt, "Fortune favors the prepared: How SMEs approach business model innovations in Industry 4.0," *Technological Forecasting and Social Change,* vol. 132, pp. 2-17, 2018, doi: https://doi.org/10.1016/j.techfore.2017.12.019.

[28] R. Ørngreen and K. Levinsen, "Workshops as a Research Methodology," *Electronic Journal of E-learning,* vol. 15, no. 1, pp. 70-81, 2017, doi: https://eric.ed.gov/?id=EJ1140102.

[29] P. Storvang, B. Mortensen, and A. H. Clarke, "Using workshops in business research: A framework to diagnose, plan, facilitate and analyze workshops," in *Collaborative research design: Working with business for meaningful findings*, P. Freytag and L. Young Eds., 2018, pp. 155-174.

[30] L. Hill, "Mentimeter: A tool for actively engaging large lecture cohorts," *Academy of Management Learning & Education,* vol. 19, no. 2, pp. 256-258, 2020, doi: https://doi.org/10.5465/amle.2019.0129.

[31] K. Vallely and P. Gibson, "Engaging students on their devices with Mentimeter," *Compass: Journal of Learning and Teaching,* vol. 11, no. 2, pp. 1-6, 2018, doi: https://doi.org/10.21100/compass.v11i2.843.

[32] D. Maxwell and M. Aitchison, "Design-value in the platform approach," in *25th Annual Conference of the International Group for Lean Construction*, Heraklion, Greece, 2017, pp. 349-356, doi: https://doi.org/10.24928/2017/0033.

[33] D. J. Teece, "Business models and dynamic capabilities," *Long range planning,* vol. 51, no. 1, pp. 40-49, 2018, doi: https://doi.org/10.1016/j.lrp.2017.06.007.

[34] D. Teece, M. Peteraf, and S. Leih, "Dynamic capabilities and organizational agility: Risk, uncertainty, and strategy in the innovation economy," *California management review,* vol. 58, no. 4, pp. 13-35, 2016, doi: https://doi.org/10.1525/cmr.2016.58.4.13.

[35] D. J. Teece, "Dynamic capabilities and (digital) platform lifecycles," in *Entrepreneurship, innovation, and platforms (Advances in Strategic Management, Vol. 37)*: Emerald Publishing Limited, 2017.

[36] J. F. Moore, "Predators and prey: a new ecology of competition," *Harvard business review,* vol. 71, no. 3, pp. 75-86, 1993, doi: http://blogs.harvard.edu/jim/files/2010/04/Predators-and-Prey.pdf.

[37] L. Stehn, S. Engström, P. Uusitalo, and R. Lavikka, "Understanding industrialised house building as a company's dynamic capabilities," *Construction innovation,* vol. 21, no. 1, pp. 5-21, 2021, doi: https://doi.org/10.1108/CI-09-2019-0086.

[38] S. Choi, I. Cho, S. H. Han, Y. H. Kwak, and Y.-Y. Chih, "Dynamic capabilities of project-based organization in global operations," *Journal of Management in Engineering,* vol. 34, no. 5, p. 04018027, 2018, doi: https://doi.org/10.1061/(ASCE)ME.1943-5479.0000621.

[39] Construction Innovation Hub, "The Product Platform Rulebook [Edition 1.2]," UK Research and Innovation, United Kingdom, 2023. [Online]. Available: https://www.constructioninnovationhub.org.uk/media/nfdfyhoj/cih-product-platform-rulebook-edition-12.pdf

IMPACT OF WORKFORCE TRAINING ON WORKER PERFORMANCE IN THE CONSTRUCTION INDUSTRY

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Abstract

For decades, labor shortage has been a consistent recurring struggle in the construction industry. A well-trained craft workforce is crucial to maximizing the worker's potential and productivity. Studies in the existing literature have highlighted the importance of workforce training and its role in mitigating the impact of widespread workforce challenges and tight labor markets. Despite that, no research has yet quantified how training impacts workers' performance. The objective of this paper is to analyze and understand the impact of workforce training on the self-evaluated performance record (including safety, attendance, quality, productivity, and initiative) of construction workers and frontline supervisors in the construction industry. To achieve the research objective, 2468 construction craft workers and frontline supervisors were surveyed using an online questionnaire. The survey participants were asked to self-evaluate their work personal performance record. The participants were additionally asked to specify how many hours of training they have completed in recent years including craft skills, job management skills, and planning skills. The collected data was then analyzed. Key findings indicate workforce training had a statistically significant impact on increased worker performance.

Peer-review under responsibility of the scientific committee of the Creative Construction Conference 2023.

Keywords: craft, performance, training, workforce.

1. Introduction and Background

The US construction industry stands at a crossroads. The aging infrastructure of the United States is in dire need of renewal as we face a major shortage of labor and craft workers [1]. The construction industry is plagued with numerous workforce challenges. The skilled craft labor shortage has been a consistent and unfortunate recurring struggle for the past three decades [2]. Moreover, recent trends show that the construction workforce has been aging rapidly, aggravating the labor shortage challenge and negatively impacting project performance in terms of cost, schedule, and safety [3]. Additionally, the construction industry lacks workforce diversity, particularly gender diversity, where women make up only 4% of the construction craft workforce in the US [4]. Still, the construction industry faces major headwinds regarding the treatment of women in the construction industry. A recent study found that women in construction are on average more likely to feel disrespected at work, treated unprofessionally, and be subjected to derogatory remarks [5]. Furthermore, the industry has not been able to consistently attract and retain skilled workers due to industry image problems, insufficient training, and an aging workforce [6]. Moreover, the industry still suffers from the lack of adequate supervision and failure of frontline supervisors to provide the necessary planning, information, support, and motivation [7], especially as frontline supervisors have a critical responsibility of ensuring safe and healthy work practices, and they create the missing communication link between management and the craft workforce [8], [9]. Multiple studies have extensively highlighted the importance and major influence frontline supervisors have on construction productivity [10]–[12].

The consensus by industry experts is that the construction industry will look radically different over the next 20 years [13]. With the increasing level of sophistication in the construction industry, companies are turning to innovative approaches to gain a competitive advantage [14], from attempting to increase the adoption construction technologies [15], to increasing the use as-built models to meet maintenance needs of the future [16], and highlighting the importance of workforce training [17].

Construction workers are the backbone of the construction industry, as they make up a sizable portion of overall production costs. Therefore, their performance and productivity are critical to the successful execution of construction projects [18]. An important issue facing the construction industry is the declining rate of worker productivity and performance [19]. Because construction workers play a huge role in overall productivity, it is essential to understand the determinants of what impacts their performance. Factors involving tools and construction equipment, materials, and technologies were found to have a major impact on worker performance [20]. For instance, one study examining the impact of several technologies on construction workforce performance and information access found that using several information, material, and equipment technologies offers a statistically significant improvement of average workforce performance in the construction industry [21]. Another study found that gender and ethnic crew diversity enhances worker performance and information access in the construction industry [22]. A third study that analyzed the administrative and computer skill proficiencies of construction workers showed that such skills enhance performance and information access [23]. Other determinants of worker performance and productivity include increased level of supervision [24], communication and efficient information flow [25], adequate financial compensation [24], proper work planning of construction tasks, materials, and methods [26], continuous work training and education, [24], and implementation of effective safety measures [27].

The prioritization of construction workforce training is critical to meeting construction industry needs [17]. Several studies have attempted to evaluate the benefits of craft and workforce training. For instance, [28] found that construction training has a benefit-to-cost ratio (B/C) ranging from 1.5:1 to 3.0:1. Moreover, [29] evaluated a B/C ratio of 2.7:1 for craft training, and [30] found that the B/C ratio for construction workforce training ranges from 2.8:1 to 3.1:1.

While the importance and benefits of worker training have been highlighted in existing work, no research has yet studied how craft training, job management skills training, and planning skills training impacts the worker's self-evaluated work performance. This study attempts to bridge this gap of knowledge using a survey of construction workers that investigates the number of training hours a worker has in each category and the respondent's performance record. The aim of this paper is to analyze and understand the impact of craft training, job management skills training, and planning skills training on the self-evaluated personal performance record of construction workers in the construction industry.

2. Methodology

In this study, a survey of construction workers in the US was conducted using an online questionnaire published through "Qualtrics". Among other questions, the survey asks construction workers about their self-evaluated personal performance, and the number of training hours in each of three categories: craft training, job management skills training, and planning skills training. The survey received 2468 responses from all 50 states to the questions being studied, with the responses having a gender breakdown of 94.8% male and 4.9% female. Of the survey respondents, 41% are craftspersons/ journeymen, 14% are foremen, 13% are apprentices/helpers, 13% are superintendents, 7% are general foremen, 3% are project managers, and 9% indicated that they hold another title. The breakdown of the respondents by age showed that 30% of them are over the age of 55, 25% are in the 45-54 age group, 25% are in the 35-44 age group, 17% are in the 25-34 age group, and 3% are under the age of 25.

The survey asked construction workers the following question relating to their performance record:

- For the last year, please rate your personal performance record (including safety, attendance, quality, productivity, and initiative) on a scale from 0 to 10, 0 being "weak", and 10 being "superior".

The survey additionally asked construction workers about the number of training hours in each of three categories: craft training, job management skills training, and planning skills training. The respondents were asked to input their response using a slider ranging from 0 hours to 200 hours, with an increment of 20 hours. If they have more than 200 hours of training, they were asked to select 200.

- How many hours of craft training and craft skill updating have you had in the last 3 years? (Including re-certification and safety).
- How many combined hours of training have you had in job management skills in the last 3 years? (Crew coordination, inter-and intra- craft coordination, selection of work packages, and leadership) (Include FORMAL on-the-job training).
- How many total hours of training have you had in planning skills in the last 3 years? (Material, equipment, tools and information request, short-term planning, and scheduling) (Include FORMAL on-the-job training).

To measure if training hours in each category has an impact on the personal performance record, the average personal performance record is calculated for each total number of training hours for each group. The Kendall tau-b correlation coefficient was used to test if there is a relationship between the total number of training hours in each category and the average personal performance record. The p-value of the Kendall tau-b correlation coefficient is obtained and compared to the significance level, α, of 0.1.

3. Results and Analysis

The average personal performance record of workers based on the total number of training hours in craft, job management skills, and planning skills training, is presented in Tables 1 through 3. Each table shows the average personal performance record for each total number of training hours. The results presented show the Kendall Tau-b correlation coefficient and the p-value of the Kendall Tau-b to examine if there is a relationship between the number of training hours and the personal performance record, and if that relationship is statistically significant.

Table 1 shows the average personal performance record for the total number of craft training hours.

Table 1 Average personal performance record for the total number of craft training hours (Sample Size = 2468)

Craft Training Hours	Average Personal Performance Record
0	8.530
20	8.541
40	8.499
60	8.592
80	8.568
100	8.444
120	8.554
140	9.043
160	8.750
180	8.682
200	8.684
Kendall Tau-b	*0.4545*
P-Value	*0.0601**

**Kendall Tau-b is statistically significant*

The correlation analysis in Table 1 was carried out to examine if there is any relationship between the total number of craft training hours a worker has and their average personal performance record. The results of the analysis show a modest positive Kendall tau-b correlation coefficient of 0.4545 between the number of craft training hours and the average personal performance record of the construction workforce. This means that an increase in the number of craft training hours is likely to increase the respondent's average personal performance record. The p-value of the Kendall tau-b is 0.0601 indicating that the correlation coefficient is statistically significant.

Table 2 shows the average personal performance record for the total number of job management skills training hours.

Table 2 Average personal performance record for the total number of job management skills training hours (Sample Size = 1817)

Job Management Skills Training Hours	Average Personal Performance Record
0	8.359
20	8.486
40	8.534
60	7.965
80	8.587
100	8.488
120	8.449
140	8.800
160	8.674
180	8.955
200	9.013
Kendall Tau-b	*0.6364*
P-Value	*0.0057**

**Kendall Tau-b is statistically significant*

The correlation analysis in Table 2 was carried out to examine if there is any relationship between the total number of job management skills training hours a worker has and their average personal performance record. The results of the analysis show a slightly strong positive Kendall tau-b correlation coefficient of 0.6364 between the number of job management skills training hours and the average personal performance record of the construction workforce. This means that an increase in the number of job management skills training hours is likely to increase the respondent's average personal performance record. The p-value of the Kendall tau-b is 0.0057 indicating that the correlation coefficient is statistically significant.

Table 3 shows the average personal performance record for the total number of planning skills training hours.

The correlation analysis in Table 3 was carried out to examine if there is any relationship between the total number of planning skills training hours a worker has and their average personal performance record. The results of the analysis show a weak positive Kendall tau-b correlation coefficient of 0.2728 between the number of planning skills training hours and the average personal performance record of the construction workforce. This means that an increase in the number of planning skills training hours is likely to increase the respondent's average personal performance record. However, the p-value of the Kendall tau-b is 0.2830 indicating that the correlation coefficient is not statistically significant. Therefore, no definitive conclusions can be made about the relationship between the number of planning skills training hours and the personal performance of a construction worker.

Table 3 Average personal performance record for the total number of planning skills training hours (Sample Size = 1968)

Planning Skills Training Hours	Average Personal Performance Record
0	8.463
20	8.344
40	8.617
60	8.525
80	8.479
100	8.444
120	8.360
140	8.750
160	8.417
180	9.000
200	8.983
Kendall Tau-b	*0.2728*
P-Value	*0.2830*

**Kendall Tau-b is statistically significant*

4. Conclusion, Limitations, and Future Work

The construction industry has been increasingly focusing on workforce training in an effort to improve productivity and enhance worker performance. While research has extensively studied and highlighted the importance of workforce training, little existing work has studied its direct impact on worker and performance. The objective of this paper is to analyze and understand the impact of craft training, job management skills training, and planning skills training on the worker's self-evaluated personal performance record in the construction industry. Using data from a survey of 2468 construction workers, correlation analysis showed that there is a statistically significant positive correlation between the average personal performance record and the number of hours of 1) workforce craft training and 2) job management skills training.

While this study presents a correlation analysis of the impact of workforce training on worker performance, the study does have certain limitations. The survey of construction workers does not ask any multiple-choice detailed questions or open-ended questions that discuss specific types of training, training techniques, worker experience and perception of the training process, or factors that resulted in enhanced access to information and performance. Therefore, while this analysis can empirically measure a positive impact on performance, the study cannot answer the questions related to why workforce training resulted in improvements. Future research can build on this study and attempt to answer these specific questions, to create a roadmap for the leaders of the construction industry to identify pathways that build the skillset of the workforce that will maximize potential benefits based on their specific construction needs.

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References

[1] Construction Industry Institute, "Workforce 2030: What You Need to Know Now About Your Future Workforce," Construction Industry Institute, Austin, TX, US, Final Report FR-370, 2021.

[2] Construction Industry Institute, "Is There a Demographic Labor Cliff that Will Affect Project Performance," Construction Industry Institute, Austin, TX, RT-318-11, 2016.

[3] T. Taylor, H. Karimi, P. Goodrum, and M. Albattah, "Is There a Demographic Labor Cliff that Will Affect Project Performance," Construction Industry Institute, Austin, TX, RT-318-1, 2016.

[4] US Bureau of Labor Statistics, "Employed Persons by Detailed Occupation, Sex, Race, and Hispanic or Latino Ethnicity," 2021. https://www.bls.gov/cps/cpsaat11.htm

[5] B. A. Ramadan, T. R. B. Taylor, K. J. Real, and P. Goodrum, "The Construction Industry from the Perspective of the Worker's Social Experience," in *Construction Research Congress 2022*, Arlington, Virginia: American Society of Civil Engineers, Mar. 2022, pp. 611–621. doi: 10.1061/9780784483985.062.

[6] R. L. Tucker *et al.*, "Key Workforce Challenges Facing the American Construction Industry An Interim Assessment," Center for Construction Industry Studies, Report No. 3, 1999.

[7] G. A. Howell, "What is Lean Construction? IGLC7," *University of California, Berkeley, CA, USA*, 1999.

[8] B. Ramadan, H. Nassereddine, T. R. B. Taylor, K. Real, and P. Goodrum, "Impact of Skill Proficiencies on Frontline Supervision Practices in the Construction Industry," in *Proceedings of the Creative Construction e-Conference (2022)*, 2022. doi: https://doi.org/10.3311/CCC2022-024.

[9] B. O. Uwakweh, "Effect of Foremen on Construction Apprentice," *J. Constr. Eng. Manage.*, vol. 131, no. 12, pp. 1320–1327, Dec. 2005, doi: 10.1061/(ASCE)0733-9364(2005)131:12(1320).

[10] N. Gerami Seresht and A. R. Fayek, "Factors influencing multifactor productivity of equipment-intensive activities," *IJPPM*, vol. 69, no. 9, pp. 2021–2045, Jul. 2019, doi: 10.1108/IJPPM-07-2018-0250.

[11] K. N. Hewage, A. Gannoruwa, and J. Y. Ruwanpura, "Current status of factors leading to team performance of on-site construction professionals in Alberta building construction projects," *Can. J. Civ. Eng.*, vol. 38, no. 6, pp. 679–689, Jun. 2011, doi: 10.1139/l11-038.

[12] M. Liberda, J. Ruwanpura, and G. Jergeas, "Construction Productivity Improvement: A Study of Human, Management and External Issues," in *Construction Research Congress*, Honolulu, Hawaii, United States: American Society of Civil Engineers, Mar. 2003, pp. 1–8. doi: 10.1061/40671(2003)5.

[13] M. J. Ribeirinho *et al.*, "The Next Normal in Construction: How disruption is reshaping the world's largest ecosystem," McKinsey & Company, 2020.

[14] A. Renz, M. Z. Solas, M. Buhler, P. Gerbert, S. Castagnino, and C. Rothballer, "Shaping the Future of Construction. A Breakthrough in Mindset and Technology," World Economic Forum, Cologny, Switzerland, 2016.

[15] G. B. Dadi, H. Nassereddine, T. R. Taylor, R. Griffith, and B. Ramadan, "Technological Capabilities of Departments of Transportation for Digital Project Management and Delivery," No. NCHRP Project 20-05, Topic 52-19, 2022.

[16] H. Nassereddine, B. Ramadan, Y. Li, R. Sturgill, and P. Patel, *Practices for the Collection, Use, and Management of Utility As-Built Information*. Washington, D.C.: Transportation Research Board, 2023, p. 27034. doi: 10.17226/27034.

[17] R. H. Assaad, I. H. El-adaway, M. Hastak, and K. LaScola Needy, "The Impact of Offsite Construction on the Workforce: Required Skillset and Prioritization of Training Needs," *J. Constr. Eng. Manage.*, vol. 148, no. 7, p. 04022056, Jul. 2022, doi: 10.1061/(ASCE)CO.1943-7862.0002314.

[18] C. S. Okoro, I. Musonda, and J. Agumba, "Identifying Determinants of Construction Worker Performance on Construction Sites: A Literature Review," *IJIMT*, pp. 60–63, 2017, doi: 10.18178/ijimt.2017.8.1.703.

[19] M. E. Shehata and K. M. El-Gohary, "Towards improving construction labor productivity and projects' performance," *Alexandria Engineering Journal*, vol. 50, no. 4, pp. 321–330, Dec. 2011, doi: 10.1016/j.aej.2012.02.001.

[20] J. Dai, P. M. Goodrum, and W. F. Maloney, "Construction Craft Workers' Perceptions of the Factors Affecting Their Productivity," *J. Constr. Eng. Manage.*, vol. 135, no. 3, pp. 217–226, Mar. 2009, doi: 10.1061/(ASCE)0733-9364(2009)135:3(217).

[21] B. Ramadan, H. Nassereddine, T. R. B. Taylor, and P. Goodrum, "Impact of Technology Use on Workforce Performance and Information Access in the Construction Industry," *Frontiers in built environment*, 2023, doi: 10.3389/fbuil.2023.1079203.

[22] B. Ramadan, H. Nassereddine, T. Taylor, and P. Goodrum, "Impact of Crew Diversity on Worker Information Access and Performance," in *ISARC. Proceedings of the International Symposium on Automation and Robotics in Construction*, IAARC Publications, 2023.

[23] B. Ramadan, H. Nassereddine, T. R. B. Taylor, and P. Goodrum, "Impact of Administrative and Computer Skill Proficiency on Workforce Performance and Information Access in the Construction Industry," in *2023 Canadian Society of Civil Engineers Annual Conference*, 2023.

[24] J. K. Yates, *Global engineering and construction*. John Wiley & Sons, 2006.

[25] H. Lingard, K. Brown, L. Bradley, C. Bailey, and K. Townsend, "Improving Employees' Work-Life Balance in the Construction Industry: Project Alliance Case Study," *J. Constr. Eng. Manage.*, vol. 133, no. 10, pp. 807–815, Oct. 2007, doi: 10.1061/(ASCE)0733-9364(2007)133:10(807).

[26] U. C. Gatti and G. C. Migliaccio, "A study on the influence of construction workers' physiological status and jobsite environment on behaviour and performance," in *49th ASC Annual International Conference Proceedings*, Citeseer, 2013, pp. 10–13.

[27] A. Enshassi, S. Mohamed, and S. Abushaban, "Factors Affecting The Performance of Construction Projects in the Gaza Strip," *JOURNAL OF CIVIL ENGINEERING AND MANAGEMENT*, vol. 15, no. 3, pp. 269–280, Jun. 2009, doi: 10.3846/1392-3730.2009.15.269-280.

[28] Y. Wang, P. M. Goodrum, C. Haas, R. Glover, and S. Vazari, "Analysis of the benefits and costs of construction craft training in the United States based on expert perceptions and industry data," *Construction Management and Economics*, vol. 28, no. 12, pp. 1269–1285, Dec. 2010, doi: 10.1080/01446193.2010.524238.

[29] S. G. Brandenburg, C. T. Haas, and K. Byrom, "Strategic Management of Human Resources in Construction," *J. Manage. Eng.*, vol. 22, no. 2, pp. 89–96, Apr. 2006, doi: 10.1061/(ASCE)0742-597X(2006)22:2(89).

[30] M. P. Pappas, *An assessment of implementation requirements for the Tier II construction workforce strategy*. The University of Texas at Austin, 2004.

IMPLEMENTATION OF CONSTRUCTION 4.0 TECHNOLOGIES IN THE TURKISH CONSTRUCTION INDUSTRY

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Abstract

The construction industry is one of the world's precursors in labor force development and economic engagement. However, it confronts with several challenges. The digital revolution might provide some solutions to the encountered problems in the construction industry, which is traditionally slow to adopt the efficiency afforded by information technologies. There are numerous studies focused on the challenges faced by the construction industry. However, there need to be more studies investigating the level of construction professionals' recognition level of new technologies and their expectations regarding the problem-solving capabilities of Construction 4.0 technologies. This study aims to fill this gap by summarizing Construction 4.0 technologies, encountered problems in the construction industry, and the expected benefits from these technologies while comparing the perceptions of different groups of respondents' companies. Based on a comprehensive literature review, 13 Construction 4.0 technologies, 11 main problems encountered in construction projects, and 17 expected benefits from Construction 4.0 technologies were identified, and a questionnaire was developed. The questionnaire data obtained from 188 Turkish construction professionals were analyzed using a mean score analysis. According to the study's findings, medium/large size companies rated the recognition level of Construction 4.0 technologies and expected benefits of these technologies higher than micro/small firms, while they gave lower ratings for the main problems in construction projects. Additionally, construction firms working mainly on international projects gave higher ratings for Construction 4.0 technologies and main problems, while national and international enterprises had similar expectations for Construction 4.0's benefits. Likewise, enterprises with IT employees ranked Construction 4.0 technologies and the main problems in construction projects higher than those without IT staff, and the expected benefits of Construction 4.0 technologies were very similar. The findings of this study may guide construction professionals in deciding which innovations to support and encourage academics to create new technologies regarding real-world concerns.

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Keywords: Construction 4.0 technologies, expected benefits, problems in construction, questionnaire, Turkish construction professionals.

1. Introduction

Digitization and automation technologies introduced by the fourth industrial revolution, a.k.a. Industry 4.0, has been influencing many industries such as business services, manufacturing, finance, transport and utilities, etc. as well as the construction industry [1]. Construction 4.0 was first introduced in Germany [2] and adopted the theoretical foundation of Industry 4.0., which is characterized by technical developments. It is commonly acknowledged that the construction industry suffers from many problems such as delays, cost overruns, safety, quality and sustainability problems, disputes, low productivity, etc. New forms of technology, but especially digital technologies, can help to overcome these problems to some extent as they make the industry's operations more efficient and improve workforce capabilities [3]. However, construction professionals highly resist to the integration of these technologies into their businesses [4-6]. In the construction management literature, there are only limited sources that investigated the recognition level of Construction 4.0 technologies, the main problems encountered by the professionals in construction projects, the benefits that the professionals expect from these technologies, and whether the perspectives and perceptions of different groups of construction professionals differ from each other. These gaps raise the following research questions:

- Q1. How much do the professionals working in the construction industry recognize Construction 4.0 technologies?
- Q2. What are the main problems experienced by professionals in construction projects?
- Q3. What benefits do the professionals expect from Construction 4.0 technologies when integrated with their business processes?
- Q4. Are there any significant differences in the perspectives and perceptions of the construction professionals on the aforementioned research questions with respect to the relevant characteristics of the companies in which they are employed?

The main objective of this study is to fill this knowledge gap by answering these research questions. For this purpose, first, the previous studies on Construction 4.0 were reviewed and a questionnaire, which mainly investigates the participant professionals' recognition level of Construction 4.0 technologies, the challenges encountered in construction projects, and the expected benefits from these technologies, was designed and distributed to the Turkish construction professionals. The findings of this study may support professionals in deciding in which technology to invest and academia in developing technological innovations based on industry's actual needs.

2. Literature Review

Forcael et al. [7] conducted a literature review to determine the origin and meaning of Construction 4.0 to comprehend this idea. They reviewed 257 papers from 2014 to 2019 and aimed to identify all essential components of the Construction 4.0 concept. Perrier et al. [1] analyzed 200 research articles on construction 4.0 technologies and the phases in which they are implemented. According to the findings, most of the technologies are used during the pre-construction stages and have enormous potential for the construction phases. Schönbeck et al. [8] reviewed more than 200 articles on Construction 4.0 technologies and found that there was no notable rise in the number of journal articles about new technologies from 2015 to 2019. Newman et al. [9] analyzed the literature on Industry 4.0 and related construction technologies, and conducted a case study on the advantages and disadvantages of implementing these technologies and discovered that human reaction is one of the hurdles to technology implementation and that Building Information Modelling (BIM) is the most extensively utilized technology in the construction industry. Yang et al. [10] conducted a literature study of important leadership competencies in the framework of Construction 4.0 for directing digital transformation and identified 22 key competencies for leaders based on 21 articles. Craveiroa et al. [11] reviewed mainly additive manufacturing, whereas Sepasgozar [12] examined this concept in the context of the digital twin and distinguished it from other 3D modelling methods. Calvetti et al. [13] stated the Worker 4.0 concept, which includes workers and ambient factors that may be monitored by sensor technology, hence enhancing safety and productivity. Begić and Galić [14] analyzed Construction 4.0 inside BIM 4.0 and claimed that most of the Construction 4.0 technologies are interrelated. Osunsanmi et al. [15] surveyed South African construction professionals regarding their understanding, readiness, and perception of the significance of implementing construction 4.0 ideas. Hossain and Nadeem [16] studied the incorporation of the Construction 4.0 concept in enterprises. However, a lack of training and digital culture serves as a barrier to adaptation. According to a survey conducted by Osunsanmi et al. [17] with 91 construction professionals in South Africa, the construction industry is willing to implement Construction 4.0 technologies. However, the likelihood of extensive integration of the technologies into the construction industry is limited, most likely because of a lack of understanding of the technologies. According to a case study by García de Soto et al. [6], Construction 4.0 will evolve and generate new professions in the construction industry. They found that traditional construction processes and automated systems will coexist up to a point in the future. Aghimien et al. [18] conducted a questionnaire in South Africa to examine the digitalization of construction organizations through an example of digital partnership. Muñoz-La Rivera et al. [5] investigated the "methodological-technological framework" for construction technologies and the most significant obstacles to applying these technologies in the construction industry.

3. Research Methodology

The methodology of this study has five phases: (1) literature review, (2) questionnaire design, (3) data collection, (4) data analysis, and (5) discussion. In the literature review phase, the most commonly used Construction 4.0 technologies, the main problems encountered in the construction industry, and the benefits expected from these technologies were identified. The most commonly used Construction 4.0 technologies include: Prefabrication and modularization (CT1), Radio Frequency Identification (RFID) (CT2), Building Information Modelling (BIM) (CT3), Internet of Things (IoT) (CT4), Internet of Services (IoS) (CT5), Big data (CT6), Cloud computing (CT7), Augmented Reality (AR) and Virtual Reality (VR) (CT8), 3D printing (CT9), Wearable technologies (CT10), Cyber Physical Systems (CPS) (CT11), Robots (CT12), and Drones (CT13) [3, 4, 17]. It is commonly acknowledged that the construction industry suffers from several severe problems. Within the scope of this study, only the problems that can be overcome by employing the Construction 4.0 technologies are identified. These problems can be summarized as follows: Low productivity of labourers (MP1), Ineffective usage of machinery (MP2), Delays (MP3), Cost overruns (MP4), Communication problems among stakeholders (MP5), Interrupted information flow between construction site and office (MP6), HSE problems (MP7), Clashes in design documents and constructability problems (MP8), Material wastes (MP9), Quantity take-off errors (MP10), and Reworks due to quality problems (MP11) [4,11,19,20]. Having identified the Construction 4.0 technologies and main problems mostly encountered in the construction industry, the benefits that the construction professionals expect from these technologies were investigated. These benefits include: Increased productivity (EB1), Effective usage of machinery (EB2), Time savings (EB3), Cost savings (EB4), Improved information flow between construction site and office (EB5), Obtaining real-time information on the project's progress (EB6), Quick response to the encountered problems in the project (EB7), Increasing safety (EB8), Timely detection of inadequacies of the project (EB9), Minimizing waste amount (EB10), Improving sustainable operations (EB11), Reducing human errors (EB12), Enhancing quality (EB13), Easy access to places where human access is difficult (EB14), Increasing customer satisfaction (EB15), Achieving competitive advantage in the market (EB16), and Being a pioneer in the market (EB17) [15, 19, 21-23].

In the light of the information gathered from the literature review, a questionnaire was designed. The questionnaire's main body was divided into three sections. The first section was intended to learn about the respondent professionals' recognition level of Construction 4.0 technologies using a scale of 1 – 3, where "1" - "Unaware," "2" - "Neither aware or unaware," and "3" - "Aware". In the second section, respondents were asked to identify the importance of the pre-identified problems in their projects. In order to evaluate the importance of each problem, an ordinal five-point Likert scale was adopted (1– not important, 2 – slightly important, 3 – moderately important, 4 – very important, and 5 – extremely important). The third section was intended to learn about the respondents' expectations from the Construction 4.0 technologies using a scale of 1 – 5 (1– very low, 2 – low, 3 – medium, 4 – high, and 5 – very high). The questionnaire was designed using Google Forms and the survey link was delivered electronically to over 2500 respondents in Turkey with the help of the Union of Chambers of Turkish Engineers and Architects (UCTEA). A total of 193 responses were collected, and out of 193 responses, 5 questionnaires were eliminated due to invalid responses or incompleteness. 50.53% of the respondent companies employed less than 250 technical and administrative staff (CS1) and 49.47% of them employed more than 250 technical and administrative staff (CS2). 38.30% of them operated only in national market (MR1) whereas 61.70% of them mostly operated in international markets (MR2). 49.47% of the respondent companies did not employ IT staff (IT1) and the remaining 50.53% of them employed IT staff (IT2).

4. Findings

4.1. Results of Mean Score Analysis on Construction 4.0 Technologies

The results of the mean score analysis for all respondents (see Table 1) revealed that "Internet of Services (IoS)" (CT 5), "Drones" (CT 13), and "Cloud computing" (CT 7) were ranked as the three most recognized Construction 4.0 technologies in descending order. All groups below “company scale” (CS) (e.g., CS 1 and CS 2), “the market region in which the firm predominantly operates” (MR) (e.g., MR 1 and MR 2), and "IT staff availability in the firm" (IT) (e.g., IT 1 and IT 2) ranked the top three most well-known Construction 4.0 technologies in the same order of all respondents.

Table 1. Mean score analysis of construction 4.0 technologies (CTs)

CTs	Overall Respondents (N=188)		Company Scale				Market Region				IT Staff			
	Mean	Rank	CS1 (N=95)	Rank	CS2 (N=93)	Rank	MR1 (N=72)	Rank	MR2 (N=116)	Rank	IT1 (N=93)	Rank	IT2 (N=95)	Rank
CT1	2.346	5	2.326	5	2.366	5	2.208	5	2.431	5	2.269	5	2.421	5
CT2	1.697	12	1.621	12	1.774	12	1.528	12	1.802	12	1.570	12	1.821	12
CT3	2.277	6	2.147	7	2.409	4	1.972	7	2.466	4	2.075	6	2.474	4
CT4	2.170	7	2.158	6	2.183	7	2.014	6	2.267	7	2.043	7	2.295	7
CT5	2.707	1	2.737	1	2.677	1	2.653	1	2.741	1	2.710	1	2.705	1
CT6	1.824	11	1.758	11	1.892	10	1.737	10	1.879	11	1.753	11	1.895	10
CT7	2.473	3	2.495	3	2.452	3	2.417	3	2.509	3	2.430	3	2.516	3
CT8	1.963	8	1.916	8	2.011	8	1.917	8	1.991	8	1.914	8	2.011	8
CT9	2.367	4	2.400	4	2.333	6	2.361	4	2.371	6	2.398	4	2.337	6
CT10	1.920	9	1.874	9	1.968	9	1.889	9	1.940	9	1.849	9	1.989	9
CT11	1.468	13	1.432	13	1.505	13	1.319	13	1.560	13	1.409	13	1.526	13
CT12	1.840	10	1.832	10	1.849	11	1.736	11	1.905	10	1.828	10	1.853	11
CT13	2.543	2	2.505	2	2.581	2	2.500	2	2.569	2	2.505	2	2.579	2

4.2. Results of Mean Score Analysis on Main Problems Encountered in the Construction Industry

According to Table 2, the mean score analysis for all respondents, “Delays” (MP 3), “Cost overruns” (MP 4), and “Low productivity of laborers” (MP 1) were ranked as the top three problems encountered in construction projects, in descending order. Two groups under “company scale” (CS) (e.g., CS 1 and CS 2) and “the market region in which the firm predominantly operates” (MR) (e.g., MR 1 and MR 2) ranked “Delays” (MP 3) and “Cost overruns” (MP 4) in the top three problems encountered in construction projects. Moreover, the CS 1 and the MR 1 groups ranked “Low productivity of laborers” (MP 1), and the CS 2 and the MR 2 groups ranked “Communication problems among stakeholders” (MP 5) within the top three problems experienced in construction projects. Two groups within the "IT staff availability in the firm" (IT) category (e.g., IT 1 and IT 2) ranked “Delays” (MP 3) in the top three challenges encountered in construction projects. Additionally, the IT 1 group rated " Low productivity of laborers " (MP 1) and " Clashes in design documents and constructability problems " (MP 8) among the top three construction project problems, whereas the IT 2 group ranked " Cost overruns " (MP 4) and " Communication problems among stakeholders " (MP 5).

Table 2. Mean score analysis of main problems encountered in the construction industry (MPs)

MPs	Overall Respondents (N=188)		Company Scale				Market Region				IT Staff			
	Mean	Rank	CS1 (N=95)	Rank	CS2 (N=93)	Rank	MR1 (N=72)	Rank	MR2 (N=116)	Rank	IT1 (N=93)	Rank	IT2 (N=95)	Rank
MP1	2.723	3	2.800	2	2.645	4	3.083	1	2.500	4	2.860	2	2.589	5
MP2	2.234	9	2.284	9	2.183	10	2.431	9	2.115	8	2.301	9	2.168	10
MP3	2.920	1	2.853	1	2.989	1	3.001	2	2.871	1	2.892	1	2.947	2
MP4	2.851	2	2.747	3	2.957	2	3.000	3	2.759	2	2.680	4	3.021	1
MP5	2.681	4	2.621	5	2.742	3	2.903	5	2.543	3	2.677	5	2.684	3
MP6	2.560	5	2.516	7	2.602	5	2.736	6	2.450	5	2.516	7	2.600	4

MP7	2.287	8	2.484	8	2.086	11	2.709	7	2.026	11	2.505	8	2.074	11
MP8	2.559	6	2.653	4	2.462	7	2.917	4	2.336	7	2.688	3	2.432	7
MP9	2.548	7	2.526	6	2.570	6	2.708	8	2.448	6	2.581	6	2.516	6
MP10	2.223	10	2.180	10	2.269	8	2.403	10	2.112	9	2.247	10	2.200	8
MP11	2.202	11	2.179	11	2.226	9	2.375	11	2.095	10	2.226	11	2.179	9

4.3. Results of Mean Score Analysis on Expected Benefits from Construction 4.0 Technologies (EBs)

The mean score analysis for the overall respondents presented in Table 3 indicated that “Obtaining real-time information on the project’s progress” (EB 6), “Improved information flow between construction site and office” (EB 5), “Being a pioneer in the market” (EB 17) were ranked as the top three expected benefits from Construction 4.0 technologies, in descending order. Two groups under “company scale” (CS) (e.g., CS 1 and CS 2), “the market region in which the firm predominantly operates” (MR) (e.g., MR 1 and MR 2), and "IT staff availability in the firm" (IT) (e.g., IT 1 and IT 2) ranked “Obtaining real-time information on the project’s progress” (EB 6) and “Improved information flow between construction site and office” (EB 5) among the top three expected benefits from Construction 4.0 technologies. Moreover, “Quick response to the encountered problems in the project” (EB 7) by the CS 1 and the IT 2 groups, “Being a pioneer in the market” (EB 17) by the CS 2, the MR 2, and the IT 1 groups graded inside the top three expected benefits from Construction 4.0 technologies in construction projects, while “Easy access to places where human access is difficult” (EB 14) ranked by the MR 1 group.

Table 3. Mean score analysis of expected benefits from Construction 4.0 technologies (EBs)

EBs	Overall Respondents (N=188)		Company Scale				Market Region				IT Staff			
	Mean	Rank	CS1 (N=95)	Rank	CS2 (N=93)	Rank	MR1 (N=72)	Rank	MR2 (N=116)	Rank	IT1 (N=93)	Rank	IT2 (N=95)	Rank
EB1	3.803	8	3.811	8	3.801	7	3.794	10	3.810	7	3.742	8	3.863	7
EB2	3.862	5	3.876	5	3.849	5	3.903	6	3.836	6	3.806	6	3.916	5
EB3	3.702	12	3.632	12	3.774	10	3.821	8	3.629	13	3.634	12	3.770	10
EB4	3.351	17	3.200	17	3.505	15	3.361	17	3.350	16	3.183	17	3.516	15
EB5	4.000	2	4.042	2	3.957	2	4.042	2	3.974	2	3.989	2	4.011	2
EB6	4.191	1	4.211	1	4.172	1	4.236	1	4.164	1	4.226	1	4.158	1
EB7	3.910	4	3.937	3	3.882	4	3.935	4	3.897	4	3.892	4	3.928	3
EB8	3.410	15	3.337	16	3.484	16	3.472	15	3.371	15	3.366	16	3.453	16
EB9	3.851	6	3.874	6	3.828	6	3.861	7	3.845	5	3.828	5	3.874	6
EB10	3.378	16	3.432	15	3.323	17	3.431	16	3.345	17	3.387	15	3.368	17
EB11	3.569	14	3.568	13	3.570	14	3.722	13	3.474	14	3.602	13	3.537	14
EB12	3.649	13	3.505	14	3.799	8	3.667	14	3.638	12	3.527	14	3.768	11
EB13	3.718	10	3.690	9	3.753	12	3.819	9	3.657	10	3.656	11	3.779	9
EB14	3.814	7	3.832	7	3.796	9	3.944	3	3.733	8	3.796	7	3.832	8
EB15	3.707	11	3.687	10	3.731	13	3.792	11	3.655	11	3.720	9	3.695	13
EB16	3.723	9	3.684	11	3.763	11	3.736	12	3.716	9	3.699	10	3.747	12
EB17	3.915	3	3.895	4	3.935	3	3.931	5	3.905	3	3.903	3	3.926	4

5. Conclusions

The purpose of this study was to examine the recognition level of Construction 4.0 technologies, the principal problems encountered by professionals in construction projects, the anticipated benefits of these technologies, and whether the perceptions and perspectives of different groups of construction companies vary for these subjects. For this purpose, a questionnaire survey was conducted and 188 duly completed questionnaires were collected from Turkish construction professionals. The mean score analysis method was used to determine how different groups varied about recognition level of

Construction 4.0 technologies, the main problems encountered in construction projects, and the anticipated benefits of these technologies. Although some of the recognized Construction 4.0 technologies, the challenges encountered in construction projects, and the expected benefits from these technologies evaluated similarly by all the groups, others were ranked differently, and some of them were only ranked among the top three for a certain group. The findings of this study may guide construction professionals in deciding which innovations to support and encourage academics to create new technologies regarding real-world concerns.

References

[1] N. Perrier, A. Bled, M. Bourgault, N. Cousin, C. Danjou, R. Pellerin and T. Roland, "Construction 4.0: A Survey of Research Trends," Journal of Information Technology in Construction (ITcon), pp. 416-437, 2020, doi: 10.36680/j.itcon.2020.024.
[2] R. Berger, "Digitization in the Construction Industry: Building Europe's Road to "Construction 4.0"," Roland Berger GMBH: Munich, pp. 16, Jun. 2016.
[3] N. Gambo, and I. Musonda, "Effect of the Fourth Industrial Revolution on Road Transport Asset Management Practice in Nigeria," Journal of Construction in Developing Countries, pp. 19-43, 2021, doi: 10.21315/jcdc2021.26.1.2.
[4] T. D. Oesterreich, and F. Teuteberg, "Understanding the Implications of Digitisation and Automation in the Context of Industry 4.0: A Triangulation Approach and Elements of a Research Agenda for the Construction Industry," Computers in Industry, pp. 121-139, 2016, doi: 10.1016/j.compind.2016.09.006.
[5] F. Muñoz-La Rivera, J. Mora-Serrano, I. Valero, and E. Oñate, "Methodological-Technological Framework for Construction 4.0," Archives of Computational Methods in Engineering, pp. 689-711, doi: 10.1007/s11831-020-09455-9.
[6] B. García de Soto, I. Agustí-Juan, S. Joss, and J. Hunhevicz, "Implications of Construction 4.0 to the Workforce and Organizational Structures," International Journal of Construction Management, pp. 205-217, 2022, doi: 10.1080/15623599.2019.1616414.
[7] E. Forcael, I. Ferrari, A. Opazo-Vega, and J. A. Pulido-Arcas, "Construction 4.0: A Literature Review," Sustainability, 2020, doi: 10.3390/su12229755.
[8] P. Schönbeck, M. Löfsjögård, and A. Ansell, "Quantitative Review of Construction 4.0 Technology Presence in Construction Project Research," Buildings, 2020, doi: 10.3390/buildings10100173.
[9] C. Newman, D. Edwards, I. Martek, J. Lai, W. D. Thwala, and I. Rillie, "Industry 4.0 Deployment in the Construction Industry: A Bibliometric Literature Review and UK-Based Case Study," Smart and Sustainable Built Environment, pp. 557-580, 2021, doi: 10.1108/SASBE-02-2020-0016.
[10] K. Yang, R. Y. Sunindijo, and C. C. Wang, "Identifying Leadership Competencies for Construction 4.0," Buildings, 2022, doi: 10.3390/buildings12091434.
[11] F. Craveiroa, J. P. Duartec, H. Bartoloa, and P. J. Bartolod, "Additive Manufacturing as an Enabling Technology for Digital Construction: A Perspective on Construction 4.0," Automation in Construction, pp. 251-267, 2019, doi: 10.1016/j.autcon.2019.03.011.
[12] S. M. Sepasgozar, "Differentiating Digital Twin from Digital Shadow: Elucidating a Paradigm Shift to Expedite a Smart, Sustainable Built Environment," Buildings, 2021, doi: 10.3390/buildings11040151.
[13] D. Calvetti, P. Mêda, M. Chichorro Gonçalves, and H. Sousa, "Worker 4.0: The Future of Sensored Construction Sites," Buildings, 2020, doi: 10.3390/buildings10100169.
[14] H. Begić, and M. Galić, "A Systematic Review of Construction 4.0 in the Context of the BIM 4.0 Premise," Buildings, 2021, doi: 10.3390/buildings11080337.
[15] T. O. Osunsanmi, C. O. Aigbavboa, and A. E. Oke, "Construction 4.0: The Future of the Construction Industry in South Africa," International Journal of Civil and Environmental Engineering, pp. 206-212, 2018.
[16] M. A. Hossain, and A. Nadeem, "Towards Digitizing the Construction Industry: State of the Art of Construction 4.0," Proceedings: 10th International Structural Engineering and Construction Conference, May. 2019, doi: 10.14455/ISEC.res.2019.184.
[17] T. O. Osunsanmi, C. O. Aigbavboa, A. E. Oke, and M. Liphadzi, "Appraisal of Stakeholders' Willingness to Adopt Construction 4.0 Technologies for Construction Projects," Built Environment Project and Asset Management, pp. 547-565, 2020, doi: 10.1108/BEPAM-12-2018-0159.
[18] D. Aghimien, C. Aigbavboa, A. Oke, W. Thwala, and P. Moripe, "Digitalization of Construction Organisations – A Case for Digital Partnering," International Journal of Construction Management, pp. 1950-1959, 2022, doi: 10.1080/15623599.2020.1745134.
[19] J. Xu, and W. Lu, "Smart Construction from Head to Toe: A Closed-Loop Lifecycle Management System Based on Iot," Proceedings: Construction Research Congress, Apr. 2018.
[20] D. T. Nguyen, L. Le-Hoai, P. B. Tarigan, and D. H. Tran, "Tradeoff Time Cost Quality in Repetitive Construction Project Using Fuzzy Logic Approach and Symbiotic Organism Search Algorithm," Alexandria Engineering Journal, pp. 1499-1518, 2022, doi: 10.1016/j.aej.2021.06.058.
[21] W. S. Alaloul, M. S. Liew, N. A. W. A. Zawawi, and I. B. Kennedy, "Industrial Revolution 4.0 in the Construction Industry: Challenges and Opportunities for Stakeholders," pp. 225-230, 2020, doi: 10.1016/j.asej.2019.08.010.
[22] A. Ebekozien, and C. Aigbavboa, "COVID-19 Recovery for the Nigerian Construction Sites: The Role of the Fourth Industrial Revolution Technologies," Sustainable Cities and Society, 2021, doi: 10.1016/j.scs.2021.102803.
[23] O. Elrefaey, S. Ahmed, I. Ahmad, and S. El-Sayegh, "Impacts of COVID-19 on the Use of Digital Technology in Construction Projects in the UAE,", 2022, doi: 10.3390/buildings12040489.

INNOVATIVE TOOLS FOR BETTER USE OF KNOWLEDGE IN FACILITY MANAGEMENT FOR CONSTRUCTION

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Abstract

Successful operation and maintenance of buildings relies on facility management (FM). Effective implementation of FM practices still poses diverse challenges. Through a comprehensive literature review, this research examines the current state of facility management and identifies the key gaps and challenges faced in this field. The findings indicate that major challenges concern inadequate information infrastructure, a lack of standardized processes, poorly identified required data, bad information quality and insufficient training. Common to the listed challenges is a need for a better management of knowledge. In this context, the paper explores the possible tools for better utilization of knowledge in management processes including centralized information sharing, continuous learning and improvement, and effective use of technology. This contribution demonstrates that the future research should focus on optimizing stakeholder engagement, streamlining processes, and supporting knowledge, enhancing cognitive requirements, and the supporting technology to make better use of knowledge in the construction industry.

Keywords: construction, facility management, knowledge, knowledge management.

1. Introduction

Facility Management (FM) is an integrated approach that helps organizations, facility managers, owners, and end-users to achieve their main objectives by ensuring the functionality of the built environment [1]. In other words, FM encompasses multiple disciplines that work together to ensure that the built environment is optimized for the people who use it. The most recent definition of facility management is "a profession that encompasses multiple disciplines to ensure functionality of the built environment by integrating people, place, process, and technology." It is interesting to note that this newest definition highlights the importance of technology, which was lacking previously [2, 3].

Facility managers require access to accurate and reliable information about building systems and components, which enables them to make informed decisions and take actions that enhance efficiency and productivity [1]. However, FM presents many challenges, including data loss, time wasted searching for information, lack of interoperability, and data inconsistency [4]. Due to the increasing demand for a high quality of life, globalization, and the development of information technology, managing properties and facilities in the built environment has become increasingly important. To meet these challenges, facility managers are constantly looking for new approaches that enable them to harness the power of technology and leverage data to improve their operations to fulfil the evolving needs of their stakeholders [5].

The Architecture, Engineering, Construction and Operation (AECO) industry and FM play a vital role in shaping the built environment and ensuring that it meets the needs of people. The rapid changes in the technology and societies affect the construction sector as well as the requirements of an efficient facility management system today. In the following section, the research presents the literature review that was used for examining the current state of facility management and identifying key gaps and challenges faced in this field.

The rest of this paper is organized as follows: Section 3 provides a comprehensive examination of the significance of knowledge management in the realm of facility management. Section 4 elaborates on the six essential steps involved in the knowledge management process. Section 5 subsequently outlines the various concepts and tools that can be leveraged for effective knowledge management. Ultimately, the paper investigates how these tools can potentially mitigate the identified gaps and challenges and improve the field of facility management within the construction sector and concludes the research.

2. Current Gaps and Challenges of Facility Management in Construction Sector

As part of a broader research investigation, a literature review and analysis were conducted by using the keywords “facility management”, “construction, and “gap” on Scopus database to detect existing research on this focus area. The inclusion criteria were English journals and conference papers. Total 97 papers were found on the database. After removing irrelevant content and private access papers, 45 articles remained.

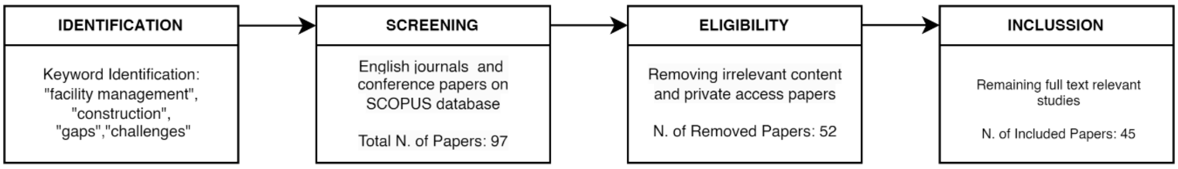

Fig. 1. Search process

Firstly, the main gaps and challenges have detected in the research, then the articles are grouped according to the gaps and challenges pointed in the research. Total five categories identified, which are the inadequate information infrastructure, the lack of standardized processes, the poorly identified required data, bad information quality, and insufficient training.

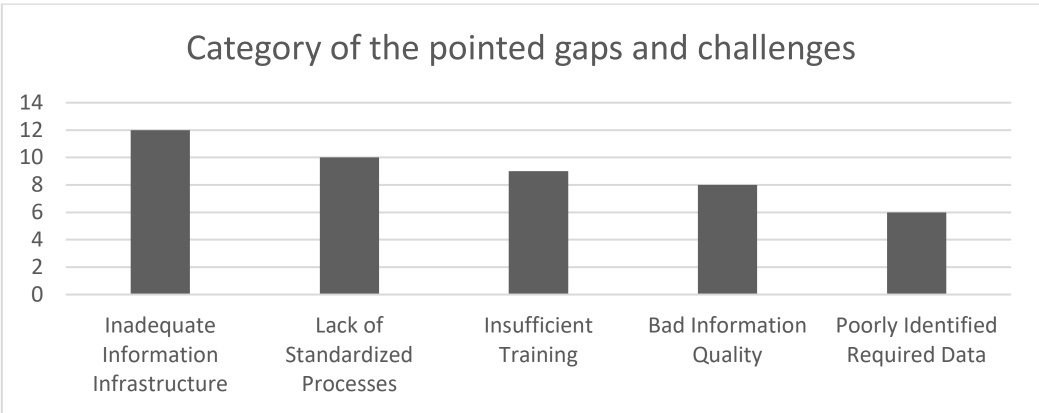

Fig. 2. Category of the pointed gaps and challenges

All the 45 papers gathered are summarized in Table 1. While 12 paper are concerning about inadequate information infrastructure, 10 papers point lack of standardized processes, 9 papers highlight insufficient training. Total 8 paper discuss bad information quality and 6 paper underline the challenges of poorly identified data. Not all papers were referenced due to limitations required on the length of this paper. The difference between the number of papers in the archive and the referenced ones can be worked out from columns no.3 and no.4 in Table 1, respectively.

Table 1. Categorization of the papers.

Category	*Sub-Category*	*N. of Total Papers*	*N. of Referenced Papers*	*Selected Referenced Papers*
Inadequate Information Infrastructure	information gap	2	1	(De Silva et al., 2017)
	integration gap	1	1	(Wang et al., 2013)
	interoperability gap	1	1	(Ozturk, 2020)
	knowledge gap	2		
	tool gap	4	1	(Wu & Lepech, 2020)
	validation gap	2		
Lack of Standardized Processes	collaboration gap	1	1	(Mehedi & Shochchho, 2021)
	information gap	3		
	interoperability gap	1		
	knowledge gap	5	2	(Kamaruzzaman et al., 2016); (Abideen et al., 2022)
Insufficient Training	awareness gap	1		
	education and training gap	5	3	(Maile et al., 2007); (Low et al., 2019); (Edirisinghe et al., 2017);
	knowledge gap	2		
	technical skills gap	1	1	(Marocco & Garofolo, 2021)
Bad Information Quality	communication gap	2	1	(Hilal et al., 2019)
	integration gap	1		
	knowledge gap	1		
	validation gap	4	1	(Chen & Tang, 2019);
Poorly Identified Required Data	collaboration gap	3	3	(Mervi, 2003); (Wen et al., 2021); (Sedhom et al. 2022)
	information gap	2	1	(Ozturk, 2020)
	validation gap	1		

One of the primary gaps identified on literature is the inadequate information infrastructure that hinders the effective management of facilities. Wang et al. (2013) emphasized the need for an integrated data source that provides information support for the building lifecycle, and the suggestion that Building Information Modelling (BIM) can fill this gap [6]. De Silva et al. (2017) pointed the gaps and lack of relationships among stakeholders, indicating a need for better communication, collaboration, and information sharing among stakeholders to achieve better value and performance in total facilities management [7]. The text also discusses the difficulty of achieving design for adaptability without the relevant information from the FM team and appropriate integration platform. Ozturk (2020) mentioned the lack of interoperability in BIM in order to increase knowledge-integrated, ontology-based, IT-based managed, collaborative, automated, well-visualized, and sustainable outcomes [8]. Wu & Lepech (2020) highlighted there exist no fundamental tools for the life-cycle management of durability performance of built structures leveraging multi-physics models and building information models (BIM) [9].

Another gap is the lack of standardized processes that hinder the effective management of building data. Mehedi & Shochchho [10] stressed lack of standardization and interoperability in the construction industry, which hampers the adoption of BIM technology. Kamaruzzaman et al. (2016) identified lack of focus on the roles of professionals and their coordination towards enhancing the implementation of BIMFM, including establishing a process workflow and guidelines [11]. Abideen et al. (2022) noted the need for a general facility maintenance knowledge database with an emphasis on the maintainability assessment at different life cycle phases and decreasing the number of maintenances interventions [12].

Insufficient training is the following challenge mentioned in literature that inhibits the efficient facility management. Maile et al. (2007) pointed educational gap among engineers and other stakeholders that needs to be overcome [13]. Low et al. (2019) stressed that future graduate students lack the soft skills needed by Industry 4.0 [14]. Edirisinghe et al. (2017) points that BIM-enabled FM is still in its infancy and has not yet reached its full potential [15]. This is partly due to the fact that organizations need to undergo a learning curve to fully implement BIM and realize its productivity gains. The text also highlights the importance of internal leadership and knowledge management in the BIM-enabled FM implementation process. Marocco & Garofolo (2021) mentioned the lack of the technical skills to manage cutting edge technology in the operational phase, especially for maintenance management [16]. They also recommend developing a platform which allows multiple FM teams to work at the same time in the same building zone by sharing information, such as position and time span of tasks and whether including potential hazards.

Bad information quality is also discussed as a challenge which obstructs the effective management of facilities for the construction sector. Hilal et al. (2019) pointed out the construction project delivery systems have enormous communication gaps, especially between the constructor and operator/owner [17]. Chen & Tang (2019) draw attention to the knowledge gap between maintenance theories and practical maintenance management in the design and construction phase [18].

Lastly, the poorly identified required data creates challenge for successful facility management. Mervi (2003) discussed the gaps between scientific information and the information needs of industry and other businesses have been a main concern of dissemination of research results. Therefore, he suggests consulting activities for co-operation between scientists and industrial partners to bridge the gap [19]. Ozturk (2020) urged the need for practical research that focuses on the full integration of cognitive technologies and the BIM platform to turn it into a digital twin of a built entity for increasing knowledge utilization for effective decision-making and efficient outcomes throughout the project lifecycle in the near future [8]. Wen et al. (2021) realized that few researchers focus on the continuous information transfer solution from the BIM model to FM systems during the building in-use phase. They also suggest an interface to be established for the “conversation” between the frequent changes of building and the FM systems in the post-construction period [20]. Sedhom et al. [21] discussed the lack of involvement and participation required by stakeholders. There is a lack of clarity in identifying the required data that is needed to manage stakeholders effectively.

These gaps and challenges have been noted by researchers across several studies, and they can be addressed through effective knowledge management. In the following chapter, we will explore in detail the ways in which knowledge management can be utilized to improve facility management practices in the construction sector. This will include a discussion of the various tools and concepts that can be implemented to ensure that the necessary knowledge is effectively created, captured, shared, and utilized, ultimately leading to better outcomes. By taking a proactive approach to knowledge management, stakeholders in the construction sector can stay ahead of the curve and improve their overall performance.

3. Knowledge Management for Facility Management

In today's dynamic and competitive environment, the ability to acquire and utilize knowledge is increasingly recognized as crucial for survival. Knowledge management (KM) is the set of methods for creating, sharing, using and managing an organization's knowledge and information [22]. Integral to knowledge management is incorporating the socio-technical perspective of people, processes, and technologies [23]. Knowledge is the most fundamental organizational resource in FM services and has the highest strategic value in understanding and managing the relationships between physical resource performance and its impact on the people they serve.[24].

The subject of knowledge opens to a particular view within FM services, starting from the conceptual chain, that links [25]:

- data (i.e., numbers, texts, images, etc.), that obtain meaning and value only in relation to a context and processing;
- information that is data processed according to specific goals, referred to a context and managed to be used, shared, and combined;
- knowledge that is the result of applying, processing, relating, combining information in specific contexts. The process, that leads information to enter in a system able to develop knowledge, creates the actual value and competitive advantage for an organization.

Fikri & Anumba [26] argue that most construction knowledge is tacit wherefore appropriate KM mechanisms must be allocated. In the realm of knowledge management, there are a variety of factors to consider, including information, communication, human resources, and intellectual capital. It involves facing a number of challenges such as usefulness of the knowledge, its transfer to others and its quantity. Therefore, effective facility management requires a range of cognitive skills such as critical thinking, problem-solving, decision-making, and analytical skills. It requires formulating and implementing strategies, improving processes, and monitoring and evaluating what knowledge exists, and its effective management. It is important yet difficult to scope, define and understand the processes, but to do so is necessary if organizations are going to be able to cope [27].

4. Knowledge Management Processes

Knowledge management is a systematic process which involves the development of policies, strategies, and tools to support the acquisition, sharing, and utilization of knowledge, with the ultimate goal of improving organizational performance and achieving strategic objectives. A well-designed set of processes is essential for successful knowledge management because they allow the business to collect, maintain, and share knowledge throughout the organization. The discourse surrounding knowledge management processes has been extensively examined by numerous scholars and has constituted the focal point of numerous investigations. From the findings of the questionnaire survey, the research of Fong & Choi confirms the six knowledge management processes namely acquisition, creation, storage, distribution, use, and maintaining [28].

1. Knowledge acquisition: It is the initial step in the knowledge management process that involves the identification and collection of knowledge from various sources. This process enables organizations to create a knowledge base that can be used for decision-making and problem-solving.

2. Knowledge creation: The process of generating new knowledge by combining existing knowledge through research, experimentation, and collaboration. This process leads to innovation and helps organizations to stay competitive.

3. Knowledge storage: The process involves organizing and preserving knowledge for future use. Knowledge is easily retrievable when needed, and it also helps to prevent information loss due to employee turnover or system failure.

4. Knowledge distribution: The process of disseminating knowledge to those who need it, whether through training programs, documentation, or other means.

5. Knowledge use: The process of applying knowledge to solve problems, make decisions, and improve organizational performance. So, the knowledge is not just stored but is utilized to make a positive impact on the organization.

6. Knowledge maintaining: It involves keeping knowledge up-to-date and relevant over time. This process ensures that knowledge does not become obsolete and is continuously improved to meet changing organizational needs.

5. Innovative Tools for Knowledge Management

Innovation in KM can be defined as an organization's willingness to apply new methods to knowledge management [29]. According to empirical findings technological, social, and organizational factors are equally important for KM processes and they show a possible categorization for innovations in the KM field [30]. The technological KM innovations are related to ICT in knowledge management systems (e.g., intranet platforms for storing knowledge) which are socio-technical systems [31]. Social innovations involve the human factor and the interaction between individuals such as motivational incentives for knowledge sharing. Moreover, organizational innovations are related to structure and hierarchy, for example, the breaking down of knowledge silos by interdisciplinary knowledge exchange groups.

The primary focus on knowledge management systems which are socio-technical systems that have the ability to assist KM processes using information and communication technology (ICT) as well as organizational and sociological theory. Schenk's research points to eight innovative concepts in the field of knowledge management which are Artificial Intelligence (AI), Big Data (BD), Communities of Practice (CoP), Digital Artifacts (DAs), Enterprise Social Media (ESM), Gamification Open Innovation (OI), and Virtual Reality (VR) [29]. The concepts range in scope and degree from practical approaches to full models (Figure 3).

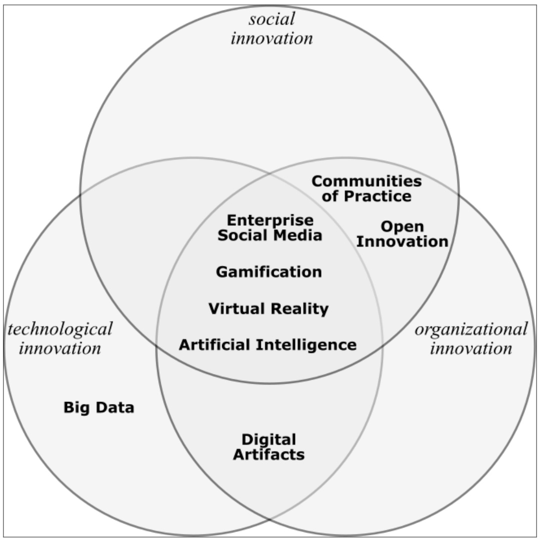

Fig. 3. Classification of identified KM concepts [29]

A variety of tools are available to support the KM concepts and processes. These include tools for accessing knowledge, which provide access to explicit knowledge that can be shared and transferred through enterprise information systems. Semantic mapping tools, including ontology tools, allow users to quickly organize and analyze information, as well as create visual representations of their research and analysis. Knowledge extraction tools support structured queries and replies and interpret relationships among different elements and documents to help with text mining. Tools for expertise localization enable quick location of knowledge holders within the enterprise and facilitate collaboration and knowledge exchange. Finally, tools for collaborative work enable teams to globally share dedicated spaces for managing project lifecycles, conducting live discussions and interactions, and maintaining a repository of materials associated with every step of the process [32].

KM tools focus on the assimilation, understanding and learning of knowledge by individuals who will transform data and information into knowledge [32]. Regardless of the amount of other individual knowledge embedded in it, the visible part of explicit knowledge is just information. Therefore, there is a need of KM tools, which can collect, categorize, organize, and share knowledge. Also, it is required to transfer information hidden in various forms and types of documents and media for facilitate information contextualization, intelligently transfer information, facilitate social interactions and networking, and present a customized human-computer interface.

Table 2 presents the web-based IT tools created by Ghani in 2009. In his study, Ghani discussed the emergence of a new group of web-based information management tools based on freeform social software that enhance individual knowledge work, group communication, and collaboration, referring to them as Web 2.0. However, more than a decade later, Web 2.0 cannot be considered a new technology and should be discussed along with many other existing KM tools.

Table 2. Web-based Information Technology Tools for Knowledge Management. (Adopted by Ghani, 2009)

Technology	Description/examples
Traditional Database Tools	These tools attempt to allow users to create general data properties implicitly within a database. They allow for the creation of objects that have certain properties, can communicate with other objects and so on.
Process Modelling and Management Tools	Processes that involve the transformation of physical material have been the focal metaphor. Tools have been built to support these processes encode considerable knowledge of the process.
Workflow Management Tools	These are the process management tools for information-intensive organizations. Workflow tools allow for the specification of the movement of documents in information processes.
Enterprise Resource Management Tools	Enterprise modelling tools are being developed to provide all the modelling capabilities of ERP/ERM systems along with the explicit representation of organizational and environmental knowledge.
Agent Tools	These tools rely on agents, relatively autonomous programs that can perform a variety of tasks. Agents may be provided with the specifications of the information that the user is interested in, and these will then search the web and specified other databases to find the information.
Search Engines, Navigation Tools, and Portals	Some of the search engines perform automatic text-only searches while others relied on human interpreters who would access web pages and then analyze and classify them.
Visualizing Tools	Tools to investigate the structure of knowledge domain and knowledge within domains. These tools have been used for data visualization in the areas of financial market to molecular biology.
Collaborative Tools	For setting of bulletin board and for real-time video conferencing, whiteboards, and chat rooms.
Web 2.0 Tools	A set of web-based tools such as wikis, blogs, tags. Social media platforms including Facebook, Twitter, Instagram, LinkedIn, and wikis, blogs, tags.

6. Discussion

The literature review has identified several technologies and tools that can be used for knowledge management. These technologies and tools can be utilized to improve facility management practices in the construction sector by addressing the identified gaps and challenges. Figure 4 shows the mapping of the tools for improving gaps and challenges in FM for the construction industry.

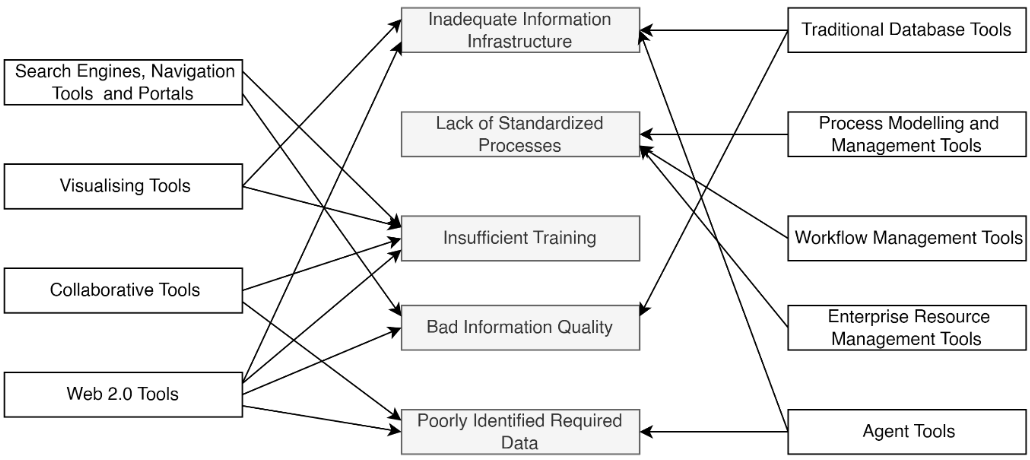

Fig. 4. Mapping of the tools for improving the gaps and challenges.

The challenge of inadequate information infrastructure can be addressed through tools such as traditional database tools and visualizing tools can be used to present complex big data in a more understandable format. Agent tools can help facility managers to process and analyze data more efficiently. Moreover, Web 2.0 tools such as social media platforms can contribute continuous communication and collaboration between the stakeholders of the projects for a better understanding of project requirements.

The lack of standardized processes can be addressed through tools such as process modelling and management tools to manage the lifecycle of documents and to create a consistent and sustainable building information flow. Workflow management tools share information and computing resources among employees, while enterprise resource management tools automate and manage core business processes for optimal performance.

Insufficient training needs to be supported by a learning system with collaborative tools, visualizing tools and Web 2.0 tools. Collaborative tools can be used to locate people by their knowledge while Web 2.0 tools provide a big support to communicate and share this knowledge. For example, social media platforms created by skilled professionals and supported by videos and visuals, such as YouTube, can provide online learning portals for students and workers.

Bad information quality in the construction project delivery systems or in the maintenance theories can be improved by search engines, navigation tools and portals with Web 2.0 tools. Search engine can be used to search the contents and to validate the relevant information, while Web 2.0 can assist with managing electronic content including multimedia files. Moreover, traditional database tools allow for the creation of objects that have certain properties, can communicate with other objects.

The challenge of poorly identified required data requires Web 2.0 tools and collaborative tools. Web 2.0 tools such as social networking sites, wikis, blogs, and video sharing platforms can facilitate participatory information sharing and communicating, while collaborative tools can be utilized to locate people by their knowledge and to ensure that the right people are involved in the management process. These processes can be supported by social media features. Professionals, workers, or students can connect and interact within the selected platforms. Agent tools may be provided with the specifications of the information that the user is interested in, and these will then search the web and specified other databases to find the information.

Overall, the tools for knowledge management can support FM processes by facilitating knowledge sharing, collaboration and communication among stakeholders, and continuous learning and improvement. By applying these tools and strategies for knowledge management, stakeholders in the construction sector can improve their overall performance and meet the emerging project needs.

7. Conclusion

There are several gaps and challenges in facility management practices in the construction industry. These challenges include inadequate information infrastructure, a lack of standardized processes, insufficient training, bad information quality and poorly identified required data, all of which require a better management of knowledge. The paper explores the possible tools for better utilization of knowledge in management processes, including centralized information sharing, continuous learning and improvement, and effective use of technology. By addressing these gaps and challenges through the utilization of various concepts, tools and strategies, stakeholders in the construction sector can improve their overall performance and meet the evolving needs. Overall, the implementation of these tools and strategies can facilitate knowledge sharing, collaboration, and communication among stakeholders and support continuous learning and improvement in FM processes. The future research should focus on optimizing stakeholder engagement, streamlining processes, and supporting knowledge, enhancing cognitive requirements, and the supporting technology to make better use of knowledge in the construction industry.

References

[1] M. Ensafi and W. Thabet, ‘Challenges and Gaps in Facility Maintenance Practices’, vol. 2, pp. 237–245, Jun. 2021.

[2] D. G. Cotts, K. O. Roper, and R. P. Payant, *The facility management handbook*, 3rd ed. New York: American Management Association, 2010.

[3] ‘What is Facility Management?’ https://www.ifma.org/about/what-is-fm/ (accessed Mar. 17, 2023).

[4] E. Yang and I. Bayapu, ‘Big Data analytics and facilities management: a case study’, *Facilities*, vol. 38, no. 3/4, pp. 268–281, Jan. 2019, doi: 10.1108/F-01-2019-0007.

[5] J. Irizarry, M. Gheisari, G. Williams, and B. N. Walker, ‘InfoSPOT: A mobile Augmented Reality method for accessing building information through a situation awareness approach’, *Autom. Constr.*, vol. 33, pp. 11–23, Aug. 2013, doi: 10.1016/j.autcon.2012.09.002.

[6] Y. Wang, X. Wang, J. Wang, P. Yung, and G. Jun, ‘Engagement of Facilities Management in Design Stage through BIM: Framework and a Case Study’, *Adv. Civ. Eng.*, vol. 2013, p. e189105, May 2013, doi: 10.1155/2013/189105.

[7] N. De Silva, R. P. N. P. Weerasinghe, H. W. N. Madhusanka, and M. Kumaraswamy, ‘Relationally integrated value networks (RIVANS) for total facilities management (TFM)’, *Built Environ. Proj. Asset Manag.*, vol. 7, no. 3, pp. 313–329, Jan. 2017, doi: 10.1108/BEPAM-08-2016-0037.

[8] G. B. Ozturk, ‘Interoperability in building information modeling for AECO/FM industry’, *Autom. Constr.*, vol. 113, p. 103122, May 2020, doi: 10.1016/j.autcon.2020.103122.

[9] J. Wu and M. D. Lepech, ‘Incorporating multi-physics deterioration analysis in building information modeling for life-cycle management of durability performance’, *Autom. Constr.*, vol. 110, p. 103004, Feb. 2020, doi: 10.1016/j.autcon.2019.103004.

[10] M. T. Mehedi and A. H. Shochchho, ‘Exploring Facility Management (7D) with BIM Considering Quality and Performance Assessment Models’, *E3S Web Conf.*, vol. 304, p. 02007, 2021, doi: 10.1051/e3sconf/202130402007.

[11] S. N. Kamaruzzaman, E. M. A. Zawawi, M. O. Shafie, and S. N. A. Mohd Noor, ‘Assessing the readiness of facilities management organizations in implementing knowledge management systems’, *J. Facil. Manag.*, vol. 14, no. 1, pp. 69–83, Jan. 2016, doi: 10.1108/JFM-01-2015-0002.

[12] D. K. Abideen, A. Yunusa-Kaltungo, P. Manu, and C. Cheung, ‘A Systematic Review of the Extent to Which BIM Is Integrated into Operation and Maintenance’, *Sustainability*, vol. 14, no. 14, Art. no. 14, Jan. 2022, doi: 10.3390/su14148692.

[13] T. Maile, M. Fischer, and R. Huijbregts, ‘The vision of integrated IP-based building systems’, *J. Corp. Real Estate*, vol. 9, no. 2, pp. 125–137, Jan. 2007, doi: 10.1108/14630010710828126.

[14] S. P. Low, S. Gao, and E. W. L. Ng, ‘Future-ready project and facility management graduates in Singapore for industry 4.0: Transforming mindsets and competencies’, *Eng. Constr. Archit. Manag.*, vol. 28, no. 1, pp. 270–290, Jan. 2019, doi: 10.1108/ECAM-08-2018-0322.

[15] R. Edirisinghe, K. A. London, P. Kalutara, and G. Aranda-Mena, ‘Building information modelling for facility management: are we there yet?’, *Eng. Constr. Archit. Manag.*, vol. 24, no. 6, pp. 1119–1154, Jan. 2017, doi: 10.1108/ECAM-06-2016-0139.

[16] M. Marocco and I. Garofolo, ‘Integrating disruptive technologies with facilities management: A literature review and future research directions’, *Autom. Constr.*, vol. 131, p. 103917, Nov. 2021, doi: 10.1016/j.autcon.2021.103917.

[17] M. Hilal, T. Maqsood, and A. Abdekhodaee, ‘A hybrid conceptual model for BIM in FM’, *Constr. Innov.*, vol. 19, no. 4, pp. 531–549, Jan. 2019, doi: 10.1108/CI-05-2018-0043.

[18] C. Chen and L. Tang, ‘BIM-based integrated management workflow design for schedule and cost planning of building fabric maintenance’, *Autom. Constr.*, vol. 107, p. 102944, Nov. 2019, doi: 10.1016/j.autcon.2019.102944.

[19] L. Mervi, ‘Multidisciplinary information management in const- ruction industry, example of facilities management’, *J. Inf. Technol. Constr. ITcon*, vol. 7, no. 14, pp. 213–244, Jun. 2003.

[20] Y. Wen, L. C. M. Tang, and D. C. W. Ho, ‘A BIM-based space-oriented solution for hospital facilities management’, *Facilities*, vol. 39, no. 11/12, pp. 689–702, Jan. 2021, doi: 10.1108/F-10-2019-0105.

[21] I. Sedhom, L. M. Khodeir, and F. Fathy, ‘Investigating current practices for achieving effective participation of stakeholders in Facilities Management’, *Ain Shams Eng. J.*, vol. 14, no. 6, p. 102099, Jun. 2023, doi: 10.1016/j.asej.2022.102099.

[22] J. Girard and J. Girard, ‘Defining knowledge management: Toward an applied compendium’, vol. 3, no. 1, 2015.

[23] N. Wickramasinghe, ‘Knowledge creation: a meta-framework’, *Int. J. Innov. Learn.*, Jul. 2006, Accessed: Feb. 22, 2023. [Online]. Available: https://www.inderscienceonline.com/doi/10.1504/IJIL.2006.010489

[24] Z. Waheed and S. Fernie, ‘Knowledge based facilities management’, *Facilities*, vol. 27, no. 7/8, pp. 258–266, Jan. 2009, doi: 10.1108/02632770910956111.

[25] C. Talamo, ‘Knowledge Management for Facility Management (FM) Services: a Rising Demand Within a Growing Market’, in *Knowledge Management and Information Tools for Building Maintenance and Facility Management*, C. Talamo and M. Bonanomi, Eds., Cham: Springer International Publishing, 2015, pp. 1–29. doi: 10.1007/978-3-319-23959-0_1.

[26] M. S. Fikri and C. J. Anumba, ‘Potential for improving site management practices through knowledge management’, *Constr. Innov.*, vol. 6, no. 4, pp. 232–249, Jan. 2006, doi: 10.1108/14714170610713917.

[27] M. Demarest, ‘Understanding knowledge management’, *Long Range Plann.*, vol. 30, no. 3, pp. 321–384, Jun. 1997, doi: 10.1016/S0024-6301(97)00017-4.

[28] P. S. W. Fong and S. K. Y. Choi, ‘The processes of knowledge management in professional services firms in the construction industry: a critical assessment of both theory and practice’, *J. Knowl. Manag.*, vol. 13, no. 2, pp. 110–126, Jan. 2009, doi: 10.1108/13673270910942736.

[29] J. Schenk, *Innovative Concepts within Knowledge Management*. 2023.

[30] R. Nowacki and K. Bachnik, ‘Innovations within knowledge management’, *J. Bus. Res.*, vol. 69, no. 5, pp. 1577–1581, May 2016, doi: 10.1016/j.jbusres.2015.10.020.

[31] A. Di Vaio, R. Palladino, A. Pezzi, and D. E. Kalisz, ‘The role of digital innovation in knowledge management systems: A systematic literature review’, *J. Bus. Res.*, vol. 123, pp. 220–231, Feb. 2021, doi: 10.1016/j.jbusres.2020.09.042.

[32] S. R. Ghani, ‘Knowledge Management: Tools and Techniques’, 2009.

MULTI-PARTY CONTRACTS IN THE VIEW OF SYSTEMS THEORY

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Abstract
Due to rising demands, Construction Management as well as Real Estate Management are recently developing into increasingly complex organisation issues. In particular, these fields are characterized by a very high degree of division of work and interdisciplinarity. Numerous participants are contributing their specific capabilities and skills as well as naturally pursue their individual goals. Traditionally, these contributors are interconnected via bilateral contracts, which are well-understood and theoretically modelled using the LEN approach. Therewith, the unavoidable incompleteness of contracts is formulated and tackled via a fundamental estimation of incentives on both sides. More recent attempts to solving the challenges coming with the rising granularization of projects like Lean Construction and Agile Methods propose multi-party contracts instead, advertising the introduction of strong common goals to all participants. The paper presented here extends the LEN model to multi-party approaches in order to estimate the required share of incentives to be distributed to the individual parties allowing for interconnected objectives and therewith common-targeted activities. This situation is investigated for different scenarios of forming the overall product, in particular for cumulative contributions as well as factorial contributions to the common objective. On this background, the fundamental, i.e., system-theoretical limits of multi-party contracts are pointed out, discussed and thoroughly evaluated.

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Keywords: Construction Management, Multi-Party Contracts, Principal-Agent Model, Real Estate Management, Systems Theory.

1. Introduction

As projects of all kinds are becoming more and more complex, i.e., comprising increasingly numerous participants, which are strongly interacting, the art of organisation is developing into the fundamental science of reducing complexity [1, 2]. System's Theory [3, 4, 5, 6] allows modelling and understanding organisational issues [7, 8, 9], where a number of interacting players are bound to achieve a common goal while pursuing individual interests [10, 11, 12]. Several theories of production have been developed on this background [13, 14, 15, 16]. Recent approaches to organisation like, e.g., Lean Construction and Lean Management [17, 18], Agile Management [19, 20], etc., refrain from introducing strong hierarchical structures [21, 22] and set a strong focus on collaboration in shallow levelled organisations. Thus, the matter-of-factly given complexity of current projects [23] is not forced into structures which are not really covering the issues but taken account of by allowing for all kind of communication. The driving force required for this to happen in a productive way is the willingness to contribute to the project goal [24], formulated in respective multi-party contracts [25].

This is the formal assignment of the classical "Allmende"-problem [26, 27], well-known in game theory, where a number of participants make use of a common limited resource in order to gain individual profit. In the end, the question of introducing incentives to act sensibly remains. The nature of incentives can be institutional rules applying sanctions or premiums as well as strategical issues or social pressure. Thus, all kinds of incentives can easily be modelled as utility functions and shares taken from the advantage of the produced good. The origin of this kind of interaction between partners is the classical bilateral contract [24, 28, 29].

Remark: In game theory, consequences and strategies have effects only locally, i.e., within the current "game" or contract, which is the "one-shot"-situation or possibly reach out to future situations, presuming a known or unknown number of repetitions [30]. In this paper we are restricting the research to the local collaboration where the findings may most likely be adjusted when investigating strategies based on multiple sequential contracts.

2. Fundamental Understanding

We assume a principal to be in charge of producing a certain well-defined good. All the required organisation as well as the design work has been done and is to be paid for accordingly, e.g., as a General Contractor. Finally, the (sub-)product needs to be produced and, hence, considered to be out-sourced to a subcontractor (agent). So far, simply, the good is to be produced at the least cost, in particular cheaper than being produced by the principal. Usually, the agent is suited better to accomplish this task through his specific expertise and the difference in cost (overall profit) is shared between the principal and the agent in order to make the bargain work. Assumedly, this (technical) share of profit due to job-specialization is already subtracted from the deal, leaving a situation where both participants are coming out equally.

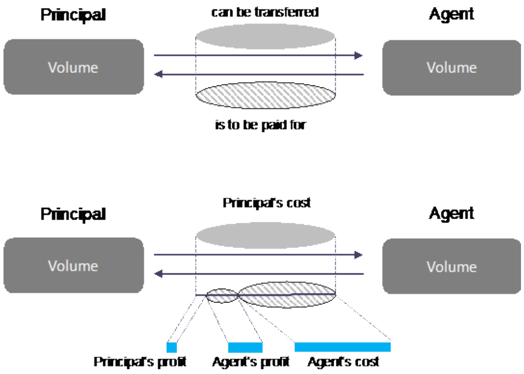

Figure 1. Fundamentals of sharing between principal and agent

However, this is true for work contracts only where a lump-sum is agreed on for a certain well-defined good. The agents' work efforts are directly transferred into the agents' profits or losses.

For service contracts, the agents' work efforts are directly impacting the efficiency which is to be paid for as a loss to the principal's side. A single work hour provides only as much result as the agent is willing to throw efforts in. Therefore, a partially fixed salary makes the agent work at all and settle the contract, however, a further variable salary proportional to the result incentivizes to increase the efforts. This may be a positive incentive like additional remuneration per result as well as a negative, e.g., by the rising thread of cancelling the contract due to low performance. Therewith, the agent's performance is coupled to the result leaving the result only to some degree with the principal while the remaining share goes to the agent.

The operating range between work contracts and pure service contracts, thus, can be formulated accordingly: The respective good of a contractually given quality is produced by the agent balanced by a fixed lump-sum while other parameters of control, e.g., duration, readiness to comply with fast organisational modifications, probably also contractually agreed-on flexibility regarding the product itself, are subjected to a variable add-on.

3. The LEN Model

The well-known LEN-model [31, 32] allows in a very fundamental way to formulate the difference between the first-best and the second-best solutions of the Principal-Agent Problem.

The focus lies on a two parties' interaction where a creation value $x = x(a, \vartheta) = \beta a + \vartheta$ is produced linearly depending on the amount of work a of the agent at the productivity β, and some random circumstances ϑ ($\overline{\vartheta} = 0\,€$, $\mathrm{var}(\vartheta) = \sigma^2$) which may reduce as well as improve the resulting creation of value. The personal discomfort of the agent $V(a) = \frac{1}{2}\eta a^2$ is understood as (negative) creation of value. The remuneration $s(x) = s_c + s_v x(a, \theta)$ of the agent is linear with the creation of value where the share represents the incentivization.

The utility functions for the principal as well as for the agent are modelled exponentially:

$$G(x) = \frac{1 - e^{-\rho(x - s(x))}}{1 - e^{-\rho(e_{\max,P})}} \text{ (Principal) and } H(x) = \frac{1 - e^{-r(s(x) - V(a))}}{1 - e^{-r(e_{\max,A})}} \text{ (Agent)} \quad (1)$$

The principal is assumed to be risk-neutral $\rho << 1$ leading to $G(x) = x - s(x)$ and the average utility $E\left[G(x)\right] = E\left[x - s(x)\right] = \left(1 - s_v\right)\beta a - s_c$

The risk within the agent's utility function is replaced by the certainty equivalent (where H_0 is the minimal benefit)

$$E\left[H(x)\right] = E\left[s(x) - V(a) - \frac{r}{2}Var(s(x))\right] = s_c + s_v \beta a - \tfrac{1}{2}\eta a^2 - \tfrac{1}{2} r s_v^2 \sigma^2 = H_0 \quad (2)$$

The remuneration would be the minimal benefit plus discomfort and certainty equivalent

$$s_c + s_v \beta a = H_0 + \tfrac{1}{2}\eta a^2 + \tfrac{1}{2} r s_v^2 \sigma^2 \quad (3)$$

Hence, the first-best solution is the principal's optimum:

$$0 = E\left[\frac{\partial}{\partial a} G(x)\right] = \beta - \eta a_{FB} \quad \Rightarrow \quad a_{FB} = \frac{\beta}{\eta} \quad (4)$$

The second-best solution preconditions unobserved working efforts allowing the agent to optimize the personal utility function

$$0 = \frac{\partial}{\partial a} E\left[H(x)\right] = s_c + s_v \beta a_{SB} - \tfrac{1}{2}\eta a_{SB}{}^2 - \tfrac{1}{2} r s_v^2 \sigma^2 = s_v \beta - \eta a_{SB} \quad \Rightarrow \quad a_{SB} = s_v \frac{\beta}{\eta} \quad (5)$$

Obviously, the working effort is reduced by the share s_v and reaches the first-best solution only if the complete creation of value is passed through to the agent (work contract situation).

On this background, the principal would optimize the utility function with respect to the optimal share s_v (with $T_{FB} = a_{FB}\beta = \beta^2 / \eta$) leading to

$$0 = E\left[\frac{\partial}{\partial s_v} G(x)\bigg|_{a_{SB} = s_v \frac{\beta}{\eta}}\right] = \frac{\beta^2}{\eta} - \eta s_v \frac{\beta^2}{\eta^2} - r s_v \sigma^2 \quad \Rightarrow \quad s_v = \frac{\beta^2 / \eta}{\beta^2 / \eta + r\sigma^2} = \frac{T_{FB}}{T_{FB} + r\sigma^2} \quad (6)$$

Comment: Risk neutrality (r = 0) or no risk existing (σ = 0) lead to s_v = 1, i.e., optimally passing through the complete production's value to the agent. This is sensible since a work contract leaves all chances and risks to the agent who exhibits, however, a risk neutral attitude. For existing risk and risk aversity (r>0) the denominator increases, the optimal share is decreasing indicating some of the risk to be left with the principal. As the certainty equivalent vanishes with reduced variance or reduced risk aversity, the share is to be increased in order to cover the minimal benefit.

4. Centralized Multi-Party Contracts – Cumulative Approach

Centralized multi-party contracts are representing situations where a central principal hands out certain parts of the production to a number of agents which are to contribute to the total creation of value. The cumulative approach models the final product as the cumulated products of the participants:

$$x_C = x_C(a_i, \vartheta)_{i=1..n} = \sum_i \beta_i a_i + \vartheta \tag{7}$$

4.1. Fundamental Equations for Cumulative Production

The first-best solution is given by the optimized utility function of the principal based on a constant utility function of the respective agent (assuming the agent receives a variable share $s_{v,j}$ proportional to the total production cumulated from the individual contributions):

$$E\left[H_j(x)\right] = s_c + s_{v,j}\sum_i \beta_i a_i - \tfrac{1}{2}\eta a_j^{\,2} - \tfrac{1}{2} r s_v^2 \sigma^2 = H_{0,j} \quad \Rightarrow \quad s_c + s_{v,j}\sum_i \beta_i a_i = H_{0,j} + \tfrac{1}{2}\eta a_j^{\,2} + \tfrac{1}{2} r s_v^2 \sigma^2 \tag{8}$$

This leads to the principal’s decision for the required work effort of the agent *j* (First Best solution):

$$0 = E\left[\frac{\partial}{\partial a_j} G(x)\right] = E\left[\frac{\partial}{\partial a_j}\left(\sum_i \left(\beta_i a_i + \vartheta\right) - \sum_i \left(H_{0,i} + \tfrac{1}{2}\eta_i a_i^{\,2} + \tfrac{1}{2} r s_v^2 \sigma^2\right)\right)\right] = \beta_j - \eta_j a_{j,FB} \quad \Rightarrow \quad a_{j,FB} = \frac{\beta_j}{\eta_j} \tag{9}$$

Comment: This is identical to the single-party contract. The optimal solution would be proportional to the individual productivity of the agent over the individual discomfort. From the investors point of view there is no difference between a single agent providing the service or a number of agents contributing to the product. The risk of agents deviating from the expected work effort is in average zero and the variance is part of the overall variance σ of a failing result.

The second-best solution rests on the optimization of the individual agent:

$$0 = \frac{\partial}{\partial a_j} E\left[H_j(x)\right] = s_c + s_{v,j}\sum_i \beta_i a_{SB,i} - \tfrac{1}{2}\eta_i a_{SB,j}^{\,2} - \tfrac{1}{2} r s_{v,j}^2 \sigma^2 = s_{v,j}\beta_j - \eta_j a_{SB,j} \quad \Rightarrow \quad a_{SB,j} = s_{v,j}\frac{\beta_j}{\eta_j} \tag{10}$$

This result also remains unchanged, based on the individual share passed through to the agent. However, the First-Best solution can only be achieved if each agent is assigned the complete profit of all individual contributions which is to be addressed in a later section.

Comment 1: The individual agent might be understood as being subjected to an additional risk derived from the unknown and inaccessible work effort of the other agents. Since only a certain share of the profit is produced by a particular agent, the remaining share is risky. Since σ^2 covers the total risk for the principal, the uncertainty of contribution of the agents is included. Hence, this total risk is to be shared between all contributors and the principal.

Comment 2: This result is sensible since a risk-neutral agent would be not affected by average positive nor negative results as long as the average is as agreed on. Only risk-averse agents would reject to share the total risk, be it a consequence of outer circumstances or other agents’ work effort.

This is correct as long as the risk is independent of the own workload, i.e., completely originated outside the system. Assuming the risk is completely formed by the other agents’ effort, some influence is possible by adjusting the own work load. Nevertheless, the impact is insignificant as a number of agents leaves only a small share of the risk to be influenced which is too little to affect the optimal solution in general.

Finally, the choice is left to the principal to decide the optimal overall share given to all agents

$$0=E\left[\frac{\partial}{\partial s_{v,j}}G(x)\bigg|_{a_{SB}=s_{v,i}\frac{\beta_i}{\eta_i}}\right]=E\left[\frac{\partial}{\partial s_{v,j}}\left(\sum_i s_{v,i}\frac{\beta_i^2}{\eta_i}+\vartheta-\sum_i\left(H_{0,i}+\tfrac{1}{2}s_{v,i}^2\frac{\beta_i}{\eta_i}^2+\tfrac{1}{2}r_is_{v,i}^2\sigma^2\right)\right)\right]=\frac{\beta_j^2}{\eta_j}-s_{v,j}\frac{\beta_j}{\eta_j}^2-r_js_{v,j}\sigma^2 \tag{11}$$

Therewith, introducing the individual share of the creation of value $T_{j,FB}=\beta_j^2/\eta_j$:

$$s_{v,j}=\frac{\beta_j^2/\eta_j}{\beta_j^2/\eta_j+r_j\sigma^2}=\frac{T_{j,FB}}{T_{j,FB}+r_j\sigma^2} \tag{12}$$

Hence, linear cumulation of production also leads to no changes to the required share (but refers to the individual contribution of agent *j*) and has no consequences beyond the cumulated agency cost. The logical consequence again would be to hand out work contracts to risk-neutral agents.

Comment: This approach does not take into account, that the complete creation of value cannot be passed through to each of the agents. The optimal share for any risk-neutral agent would equate 1 leading to a work contract for the total production while only contributing a share to it. This equals a situation with a very large lever available for each agent to be paid by the principal in addition to the creation of value via the product. This would make them highly overpaid (and risk loaded) just to make the agents work optimally.

4.2. Characteristics and Consequences Due to Multiple Agents with Focus on the Principal

The decision of the principal for the individual share based on optimizing his own utility function in this scenario implies that the complete production of value needs to be distributed to each of the *n* agents (if these are risk neutral). Hence, even the maximum second-best solution is not equal to the first-best solution but roughly limited to *1/n* if equally distributed. This perspective is to be elaborated and discussed in this section.

In order to identify the optimal distribution, the condition of sharing the profit at max on all participants needs to be taken care of while optimizing. Using the Lagrange parameter λ we modify:

$$0=E\left[\frac{\partial}{\partial s_{v,j}}\left(\sum_i s_{v,i}\frac{\beta_i^2}{\eta_i}+\vartheta-\sum_i\left(H_{0,i}+\tfrac{1}{2}s_{v,i}^2\frac{\beta_i}{\eta_i}^2+\tfrac{1}{2}r_is_{v,i}^2\sigma^2\right)+\lambda\left(1-\sum_i s_{v,i}\right)\right)\right]\;\Rightarrow\; s_{v,j}=\frac{T_{j,FB}}{T_{j,FB}+r_j\sigma^2}\left(1-\frac{\lambda}{T_{j,FB}}\right) \tag{13}$$

Hence, we obtain an expected reduction ($\lambda>0$) of share depending on the boundary condition, in particular, not as a general scaling but varying with the individual contribution.

This is to be inserted into the boundary condition:

$$1=\sum_i s_{v,i}=\sum_i\frac{T_{i,FB}}{T_{i,FB}+r_i\sigma^2}\left(1-\frac{\lambda}{T_{i,FB}}\right)=\sum_i s_{v,i,0}-\sum_i s_{v,i,0}\frac{\lambda}{T_{i,FB}}\;\Rightarrow\;\lambda=\frac{\sum_i s_{v,i,0}-1}{\sum_i s_{v,i,0}/T_{i,FB}} \tag{14}$$

Comment: The overhead share, which cannot be assigned, is distributed over all the shares weighted with their contribution

In order to provide a sensible explanation for the Lagrange parameter λ, parameters $\bar{E}$ and $\tilde{E}$ are introduced. Considering the numerator of λ yields:

$$\sum_i s_{v,i,0}=\sum_i\frac{T_{i,SB,NoBC}}{T_{i,FB}}=n\left\langle\frac{T_{i,SB}}{T_{i,FB}}\right\rangle=n\bar{E} \tag{15}$$

$\bar{E}=\langle T_{i,SB}/T_{i,FB}\rangle=\langle E_i\rangle$ represents the average efficiency reduction of all agents. Then, introducing the share $S_i=T_{i,FB}/T_{FB}$ (share of production by agent *i*) and therewith $\tilde{E}$ as the average efficiency reduction, scaled up to the total production $\tilde{E} = \left\langle \left(T_{i,SB}/T_{i,FB}\right)/\left(T_{i,FB}/T_{FB}\right)\right\rangle = \left\langle E_i / S_i \right\rangle$, the denominator is

$$\sum_i s_{v,i,0}/T_{i,FB} = \frac{n}{nT_{FB}}\sum_i \frac{T_{i,SB}}{T_{i,FB}}\frac{T_{FB}}{T_{i,FB}} = \frac{n}{T_{FB}}\left\langle \frac{T_{i,SB}}{T_{i,FB}}\frac{T_{FB}}{T_{i,FB}}\right\rangle = \frac{n}{T_{FB}}\tilde{E} \tag{16}$$

Remark: This value represents the average of the efficiency reductions of agent i if agent i were effective on the total production, i.e., if agent i were the only creator of value.

Overall, λ is simplified to:

$$\lambda = \frac{\sum_i s_{v,i,0} - 1}{\sum_i s_{v,i,0}/T_{i,FB}} = \frac{n\overline{E}-1}{n\tilde{E}/T_{FB}} = T_{FB}\frac{\overline{E}-1/n}{\tilde{E}} \tag{17}$$

Comment: λ is the average total loss stepping from First Best to Second Best solutions (minus the individual contribution of one) over the average loss if each agent would be the creator of the total value.

The averages can be expressed as follows:

$$n\overline{E} = \frac{n}{T_{FB}}\sum_i s_{v,j}\frac{T_{FB}}{n} = \frac{nT_{SB}}{T_{FB}} \quad \Rightarrow \quad \overline{E} = \frac{T_{SB}}{T_{FB}} \text{ and for equal agents } \tilde{E}^{(eq)} = \left\langle \frac{T_{i,SB}}{T_{i,FB}}\frac{T_{FB}}{T_{i,FB}}\right\rangle = \frac{1}{n}\sum_i s_{v,i,0}\frac{n}{1} = n\overline{E} = n\frac{T_{SB}}{T_{FB}}$$

The so far given constant λ is to be inserted into the computation of $s_{v,j}$:

$$s_{v,j} = \frac{T_{j,FB}}{T_{j,FB} + r_j\sigma^2}\left(1-\lambda/T_{j,FB}\right) = s_{v,j,0}\left(1-\lambda/T_{j,FB}\right) \tag{18}$$

Hence, the Lagrange parameter λ reduces the share as well as the total production. Using $\overline{E}^{(eq)} = T_{SB}/T_{FB}$, $\tilde{E}^{(eq)} = n\overline{E}^{(eq)} = nT_{SB}/T_{FB}$ and $s_{v,0} = T_{SB}/T_{FB}$, for equally contributing agents, the share of value develops into:

$$s_{v,j} = s_{v,j,0}\left(1-\frac{\lambda^{(eq)}}{T_{j,FB}}\right) = s_{v,0}\left(1-T_{FB}\frac{\overline{E}-1/n}{\tilde{E}^{(eq)}T_{j,FB}}\right) = s_{v,0}\left(1-\frac{T_{SB}-T_{FB}/n}{T_{SB}}\right) = \frac{T_{SB}}{T_{FB}}\left(\frac{T_{FB}}{nT_{SB}}\right) = \frac{1}{n} \tag{19}$$

Comment: Most remarkably, no influence of the risk attitude is left at this point (possibly only differences in attitude due to the even distribution). Obviously, the terms regarding the risk aversion r are compensated by the reduction-of-share mechanism.

On this background, the overall system is expected to run at a less than optimal state. The total production under this restriction (boundary condition BC) is:

$$\begin{aligned} T_{SB+BC} &= \sum_i a_{SB+BC}\beta = \sum_i s_{v,i,BC}\frac{\beta_i}{\eta_i}\beta_i = \sum_i s_{v,i,0}\left(1-\lambda/T_{i,FB}\right)\frac{\beta_i^2}{\eta_i} \\ T_{SB+BC} &= \sum_i s_{v,i,0}\left(1-\lambda/T_{i,FB}\right)T_{i,FB} = \sum_i s_{v,i,0}\left(T_{i,FB}-\lambda\right) = \sum_i s_{v,i,0}T_{i,FB} - \lambda\sum_i s_{v,i,0} = T_{SB} - \lambda\sum_i s_{v,i,0} \end{aligned} \tag{20}$$

With $\lambda = T_{FB}\left(\overline{E}-1/n\right)/\tilde{E}$ and using $\overline{E}^{(eq)} = T_{SB}/T_{FB}$ and $\tilde{E}^{(eq)} = n\overline{E}^{(eq)} = nT_{SB}/T_{FB}$ we obtain for equal agents as expected:

$$T_{SB+BC} = T_{SB} - T_{FB}\frac{\overline{E}-1/n}{\tilde{E}}n\overline{E} = T_{SB} - T_{FB}\frac{\overline{E}-1/n}{n\overline{E}}n\overline{E} = T_{SB} - T_{FB}\overline{E} + \frac{T_{FB}}{n} = T_{SB} - T_{SB} + \frac{T_{FB}}{n} = \frac{T_{FB}}{n} \tag{21}$$

The overall production is clearly brought down to an n^{th} of the First Best solution and furthermore independent of the risk attitude of the agents.

Remark: From this we conclude the obvious possibility to control the production in a multi-party's contract by introducing a risk independent mechanism of incentive, which, though, exceeds the result of the product by a factor of n.

Summary: We would expect the return (share) of a participant to be dependent on the effort of all contributors, while the individual effort is returned only to a degree determined by the ratio of contribution. This general aspect would lead agents to reject this concept due to being depended on all other players to a higher degree while the own effort goes mainly to others.

However, since the return is also scaled, failures as well as positive contributions obviously are balanced. The major outcome is the reduction of productivity since the incentives cannot be adjusted to the risk attitudes of the participants but in contrast need to be reduced to a degree, where mostly no incentives are in effect anymore.

Comparing this situation to the same number of bilateral contracts reveals the fundamental problem, here laid out for equal agents for simplicity: If participating in the total result as well as in the risk of the total result, the single agent requires the same share of the total result as well as he would optimally ask for with a bilateral contract for just the partial volume covered there: Sharing foreign risks demands for proportionally higher remuneration shares to compensate. Therefore, coupling a number of formerly independent bilateral (work-)contracts to an optimized cumulating multi-party contract produces additional cost of the order nT_{FB}.

5. Centralized Multi-Party Contracts – Factor Approach

In contrast to situations where the creation of value is formed by cumulative contributions, sensibly we need to consider the context where the overall value is given as the product of factors where each participant's result scales the effort of all other participants. This approach leads to production functions like

$$x_F = x_F(a_i, \vartheta)_{i=1..n} = \prod_i \beta_i a_i + \vartheta \tag{22}$$

5.1. Fundamental Equations for Factor-based Production

The first-best solution is again based on the agent's minimal utility

$$E\left[H_i(x)\right] = s_c + s_v \prod_j \beta_i a_i - \tfrac{1}{2}\eta_i a_i^2 - \tfrac{1}{2} r_i s_v^2 \sigma^2 = H_0 \quad \Rightarrow \quad s_c + s_v \prod_i \beta_i a_i = H_0 + \tfrac{1}{2}\eta_i a_i^2 + \tfrac{1}{2} r_i s_v^2 \sigma^2 \tag{23}$$

and the principal's decision for the required work effort of the agent j:

$$0 = E\left[\frac{\partial}{\partial a_j} G(x)\right] = E\left[\frac{\partial}{\partial a_j}\left(\prod_i \beta_i a_i + \vartheta - \sum_i \left(H_{0,i} + \tfrac{1}{2}\eta_i a_i^2 + \tfrac{1}{2} r_i s_{v,i}^2 \sigma^2\right)\right)\right] = \frac{1}{a_{j,FB}} \prod_i \beta_i a_i - \eta_j a_{j,FB} \quad \Rightarrow \quad a_{j,FB} = \sqrt{\frac{\prod_i \beta_i a_i}{\eta_j}} \tag{24}$$

Then, the second-best solution results from the optimization of the individual agent:

$$\begin{aligned} 0 &= \frac{\partial}{\partial a_j} E\left[H_j(x)\right] = \frac{\partial}{\partial a_j} E\left[s_c + s_{v,j} \prod_i \beta_i a_{SB,i} - \tfrac{1}{2}\eta_j a_{SB,j}^2 - \tfrac{1}{2} r_j s_{v,j}^2 \sigma^2\right] = \frac{s_{v,j}}{a_{SB,j}} \prod_i \beta_i a_{SB,i} - \eta_j a_{SB,j} \\ a_{SB,j} &= \sqrt{s_{v,j}} \sqrt{\frac{\prod_i \beta_i a_{SB,i}}{\eta_j}} = \sqrt{s_{v,j}}\, a_{FB,j} \end{aligned} \tag{25}$$

Comment: This optimization only reflects the attitude of the local agent j. Hence, it is valid, if all other participants are not changing their working effort, be it that all are doing their best or that already having optimized their effort.

In contrast to the cumulative contract, the optimal second-best working effort comes to be the first-best scaled with the square-root of the remuneration share, which is significantly less than the linear approach.

On this background, the principal decides for the optimal individual share:

$$0=E\left[\frac{\partial}{\partial s_{v,j}}G(x)\right]=E\left[\frac{\partial}{\partial s_{v,j}}\left(\prod_i \beta_i a_{SB,i}+\vartheta-\sum_i\left(H_{0,i}+\tfrac{1}{2}\eta_i a_{SB,i}{}^2+\tfrac{1}{2}r_i s_{v,i}^2\sigma^2\right)\right)_{a_{SB,i}=\sqrt{s_{v,i}}\sqrt{\frac{\prod_k \beta_k a_{SB,k}}{\eta_i}}}\right] \quad (26)$$

Introducing the actual total production $P=\prod_i \beta_i a_{SB,i}$ and therewith $\frac{\partial P}{\partial s_{v,j}}=\frac{P}{2s_{v,j}}$ we obtain

$$0=E\left[\frac{\partial}{\partial s_{v,j}}\left(P+\vartheta-\sum_i\left(H_{0,i}+\tfrac{1}{2}s_{v,i}P+\tfrac{1}{2}r_i s_{v,i}^2\sigma^2\right)\right)\right]=\frac{P}{2s_{v,j}}-\frac{3P}{4}-r_j s_{v,j}\sigma^2=\frac{P}{2}-\frac{3P}{4}s_{v,j}-r_j s_{v,j}^2\sigma^2 \quad (27)$$

Remark: For vanishing risk or neutral risk attitudes we have at this point:

$$r_j s_{v,j}^2\sigma^2=0 \quad\Rightarrow\quad 0=\frac{P}{2}-\frac{3P}{4}s_{v,j}-0 \quad\Rightarrow\quad \frac{3P}{4}s_{v,j}=\frac{P}{2} \quad\Rightarrow\quad s_{v,j}=\frac{2}{3}$$

Hence, from this second order equation we obtain two formal solutions for the individual share s for agent *j using* $R_{j,rel}=8r_j\sigma^2/P$:

$$0=\frac{P}{2}-\frac{3P}{4}s_{v,j}-r_j s_{v,j}^2\sigma^2 \quad\Rightarrow\quad 0=\frac{8P}{2P}-\frac{3\cdot 8P}{4P}s_{v,j}-\frac{8r_j\sigma^2}{P}s_{v,j}^2 \quad\Rightarrow\quad 0=4-6s_{v,j}-R_{j,rel}s_{v,j}^2 \quad (28)$$

$$s_{v,j}=-\frac{3\pm\sqrt{9+4R_{j,rel}}}{R_{j,rel}} \quad (29)$$

Comment: As stated, this value is 2/3 for vanishing risk or risk aversion, and decreasing from there. Compared to bilateral contracts or even cumulative multiparty contracts, the situation is different: Since the own impact affects the total result as a factor, the lever at the agents' side is large. Nevertheless, the risk implied by the fellow agents is large as well. Due the non-linearity of the problem, the balance turns out to be at a slightly different equilibrium share of 2/3, however, still in balance. Again, the boundary condition in this situation enforces non-optimal assignments for all participants as well.

In order to evaluate more encompassing values of the system like the total creation of value, the individual deviation of parameters, in particular the individual risk attitude from the average needs to be formulated:

$$\bar{R}_{rel}=\frac{1}{n}\sum_i R_{i,rel}=\left\langle R_{i,rel}\right\rangle \quad\Rightarrow\quad R_{j,rel}=\bar{R}_{rel}\nu_j \qquad \nu_j=1+\delta R_{j,rel}/\bar{R}_{rel}=1+\left(R_{j,rel}-\bar{R}_{rel}\right)/\bar{R}_{rel} \quad (30)$$

Hence, the average value can be used, but is corrected by an additional factor ν_j, formed by the relative deviation. For equal participants, this factor is $\nu_j=1$.

On this background, the total production using the optimized individual share can be computed.

$$P_{SB}=\prod_i \beta_i a_{SB,i}=\prod_i \beta_i\sqrt{s_{v,i}}a_{FB,i}=\prod_i\sqrt{-\frac{3\pm\sqrt{9+4R_{i,rel}}}{R_{i,rel}}}P_{FB} \;\square\; \prod_i\sqrt{-\frac{3\pm\sqrt{9+4\nu_j\bar{R}_{rel}}}{\nu_j\bar{R}_{rel}}}P_{FB} \quad (31)$$

The deviation factor can be neglected for the additive terms, i.e., set equal to 1:

$$P_{SB} \approx \left(-\frac{3\pm\sqrt{9+4\bar{R}_{rel}}}{\bar{R}_{rel}}\right)^{n/2} P_{FB}\prod_i \frac{1}{\sqrt{\nu_j}} = \left(-\frac{3\pm\sqrt{9+4\bar{R}_{rel}}}{\bar{R}_{rel}}\right)^{n/2} P_{FB} \quad \text{using} \quad \prod_j \sqrt{\nu_j}^{-1} = 1 \tag{32}$$

(restricted to a first order approximation, since the average deviation is zero per definitionem).

From the two options, obviously, only the (-)-version is permitted:

With $E=\sqrt{9+\varepsilon}>3 \quad \varepsilon>0 \quad \Rightarrow \quad s_{j,rel} = -\frac{3\pm E}{R_{i,rel}} = \begin{cases} <0 & (+) \\ >0 & (-) \end{cases}$ we use $P_{SB} \approx \left(-\frac{3-\sqrt{9+4\bar{R}_{rel}}}{\bar{R}_{rel}}\right)^{n/2} P_{FB}$ (33)

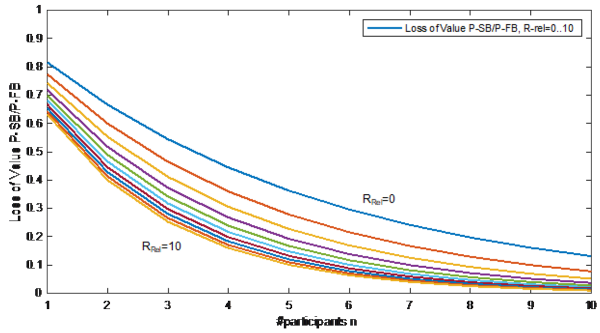

Figure 2. Loss of value with rising numbers of participants in factor approach (R_{rel}=0..10)

Remark: As stated before, the limit for vanishing $\bar{R}_{rel}$ *is* $s_{v,i} \to 2/3$*, hence the loss is* $\sqrt{2/3}=0.816$ *at n=1.*

5.2. Characteristics and Consequences Due to Multiple Agents with Focus on the Principal

Taking into account the effect of numerous contributing agents, the overall share cannot exceed the complete creation of value. This leads to the boundary condition $1=\sum_i s_{v,i}$ which must be observed, modifying the principal's optimization equations. Again, we are using a Lagrange parameter μ:

$$0 = E\left[\frac{\partial}{\partial s_{v,j}}\left(P+\vartheta-\sum_i\left(H_{0,i}+\tfrac{1}{2}s_{v,i}P+\tfrac{1}{2}r_i s_{v,i}^2\sigma^2\right)+\mu\left(\sum_i s_{v,i}-1\right)\right)\right] = \frac{P}{2}-\frac{3P}{4}s_{v,j}-r_j s_{v,j}^2\sigma^2+\mu \tag{34}$$

Using $R_{j,rel}=8r_j\sigma^2/P$ and $\mu_{rel}=8\mu/P$ yields

$$0=\frac{P}{2}-\frac{3P}{4}s_{v,j}-r_j s_{v,j}^2\sigma^2+\mu \quad \Rightarrow \quad 0=4-6s_{v,j}-R_{j,rel}s_{v,j}^2+\mu_{rel} \quad \Rightarrow \quad s_{v,j}=-\frac{3\pm\sqrt{9+R_{j,rel}(4+\mu_{rel})}}{R_{j,rel}} \tag{35}$$

In order to find a respective value for μ_{rel} these results are to be inserted into the boundary condition.

$$1=\sum_j s_{v,j} = \sum_i \frac{3\pm\sqrt{9+4R_{j,rel}+\mu_{rel}R_{j,rel}}}{-R_{j,rel}} = \sum_j \frac{\frac{3}{\nu_j}\pm\frac{\sqrt{\nu_j}}{\nu_j}\sqrt{\frac{9}{\nu_j}+4\bar{R}_{rel}+\mu_{rel}\bar{R}_{rel}}}{-\bar{R}_{rel}} \tag{36}$$

The first term is proportional to $\sum_j \frac{1}{\nu_j} = n\left\langle 1/\nu_j \right\rangle$ which equates 1 in first order development for $\nu_j \approx 1$.

$$1 \approx \sum_j \frac{3\pm\frac{1}{\sqrt{\nu_j}}\sqrt{9/\nu_j+4\bar{R}_{rel}+\mu_{rel}\bar{R}_{rel}}}{-\bar{R}_{rel}} \tag{37}$$

This can be rearranged providing the Lagrange parameter μ_{rel} using furthermore the second order development for $\nu_j \approx 1$ (The first order provides no contribution.):

$$\bar{\nu} = \left\langle 1/\nu_j^{1/2} \right\rangle = \frac{1}{n}\sum_j \frac{1}{\sqrt{\nu_j}} \approx 1 + 3\frac{3\sigma^2_{Rrel}}{8\bar{R}^2_{rel}} \tag{38}$$

$$\mu_{rel} = -\frac{9}{\nu_j \bar{R}_{rel}} - 4 \pm \frac{1}{\bar{\nu}^2}\left(\frac{\bar{R}_{rel}}{n^2} + \frac{6}{n} + \frac{9}{\bar{R}_{rel}}\right) \tag{39}$$

The Lagrange parameter inserted into $s_{v,j}$ finally allows determining the optimized individual share

$$s_{v,j} = -\frac{3 \pm \sqrt{9 + R_{j,rel}(4 + \mu_{rel})}}{R_{j,rel}} = -\frac{3 \pm \frac{1}{\bar{\nu}}\sqrt{\pm\left(\frac{R^2_{j,rel}}{n^2} + \frac{6R_{j,rel}}{n} + 9\right) + 9\left(1 - \frac{1}{\nu_j}\right)}}{R_{j,rel}} \tag{40}$$

The last term can again be neglected for small deviations from equality. Then, the remaining root must be a positive, hence, we deduce only $\mu_{rel,(+)}$ represents a real solution.

$$s_{v,j} = -\frac{3}{R_{j,rel}} \mp \frac{1}{\bar{\nu}}\left(\frac{1}{n} + \frac{3}{R_{j,rel}}\right) \Rightarrow \quad s_{v,j(+)} \approx \frac{1}{\bar{\nu} n} \qquad s_{v,j(-)} \approx -\frac{1}{\bar{\nu} n} - \frac{6}{R_{j,rel}} \tag{41}$$

Formally, two solutions for $s_{v,j}$ are determined. In order to determine the sensible option, the validity of the boundary condition is to be ensured, tested for equal participants:

$$s_{v,j(-)} = \frac{1}{n} + \frac{6}{R_{j,rel}} \Rightarrow \quad 1 = n\left(\frac{1}{n} + \frac{6}{R_{j,rel}}\right) = 1 + \frac{6n}{R_{j,rel}} \quad and \quad s_{v,j(+)} = \frac{1}{n} \Rightarrow \quad 1 = n\left(\frac{1}{n}\right) = 1 \tag{42}$$

Obviously, $s_{v,j,(-)}$ violates the boundary condition unless $n = 0$ which does not make sense or $R_{j,rel} = \infty$ which also is not sensible. This leaves only the trivial result.

The total production based on the individual share, however, including the observation of the boundary condition (BC) for equal contributions which, though, are of no relevance here, leads to:

$$P_{SB+BC} = \prod_i \beta_i a_{SB,i} = \sqrt{s_v}^n \prod_i \beta_i a_{FB,i} = \sqrt{s_v}^n P_{FB} = \left(\frac{1}{\sqrt{n\bar{\nu}}}\right)^n P_{FB} = \left(n\bar{\nu}\right)^{-n/2} P_{FB} \tag{43}$$

$$\text{and } \bar{\nu} \cong 1 + \frac{3\sigma^2_{Rrel}}{8\bar{R}^2_{rel}} \tag{44}$$

Comment: Again, the overall result becomes independent of the share and the individual risk attitude. In second order approximation some effect is caused by the variance of the risk attitudes which further reduces the total production.

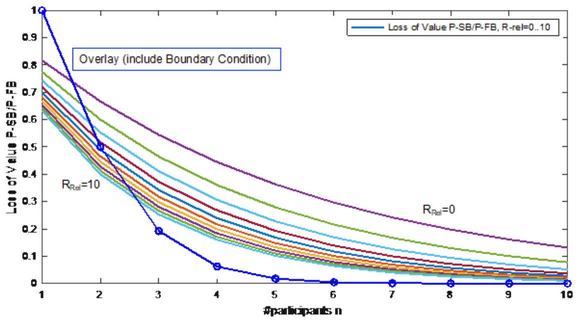

Figure 3. Overlayed loss of value with rising numbers of participants in factor approach observing the boundary condition

6. Conclusion

Any organization of projects is controlled by the strength of given incentives which are handed out to the participants. The closed model (game-theoretical one-shot situation) used here is restricted to the overall creation of value of the given project, which limits the incentives that can be distributed to the agents.

With two-party contracts the sensible share is depending on the risk attitude of the agent and determines the position in the linear space between work contracts and service contracts. In multi-party contracts, with cumulative production functions, the share required to optimize the single agents' contribution ranges from 0 to 1, with factor-based production functions from 0 to 2/3 of the total creation of value, in both cases decreasing with rising risk or risk aversion of the agents. As soon as the limit of incentives to be distributed to all agents is taken into account, in both cases the share becomes mainly independent of the risk attitudes, furthermore independent of the degree of contribution and approaches $1/n$ (cumulative) respectively $1/\sqrt{n}$ (factor based). Therewith, the total creation of value decreases to $1/n$ resp. $1/\sqrt{n}$ as well.

Remark: In this paper, only effects of linear incentives are tackled, modified by the respective Arrow-Pratt-Measure. Strongly nonlinear or even non-continuous incentivisation as might occur with strategical issues, e.g., high specificity of supply or demand, and therefrom resulting unbalanced markets may very well modify the optimal work-effort in a different way.

This result clearly points out, that the local (one-shot) incentives available with any multi-party contract are by far not providing the required volume to ensure optimal efforts for any kind of work contract, forcing the use of service contracts instead. Only in case of strongly risk-averse agents and high risks the optimal share could be handed out, however, in this case the contracts are mainly service contracts due to the risk attitudes. Multi-party contracts are based on collaboration, i.e., in particular, sharing the risk of a common goal. Thus, service contracts are not helpful, the focus lies on work contracts.

Remark: Eventually occurring non-linear incentives on the background of markets or strategical issues are typically not assigned to the project at hand but to the individual agent. Therefore, these represent no sharable risk and cannot be transferred to fellow agents or the principal.

On this background, the sensible use of multi-party contracts in one-shot environments is limited to a small number of participants. Though, even then, the created value is decreasing with the number of players which can only be compensated by introducing further incentives, which are clearly not located within the considered model. These are therefore not covered by the contract itself but created from the strategical environment (which is, e.g., immanently the case with service contracts) including non-linear individual effects. In particular, the chain store model suggests a significant impact of the contractual context, namely the opportunities provided by connected future collaborations (multi-shot chains). These external benefits, however, are bound to provide up to about the n-fold (or at least $\sqrt{n}$ -fold) value of the contract to effectuate optimal contributions.

References

[1] W. Eber, "Managing Construction Projects: Developing Complexity into Complicatedness," IOP Conference Series: Earth and Environmental Science, vol. 323, p. 012097, Sep. 2019, doi: 10.1088/1755-1315/323/1/012097.

[2] Strogatz S H 2001, "Exploring complex networks", https://doi.org/10.1038/35065725, Nature 410, p.268.

[3] N. Wiener, „Kybernetik". Düsseldorf, Germany: Econ Verlag, 1992.

[4] L. Bertalaffny, "General Systems Theory". New York, USA: George Braziller Inc., 1969, pp 54.

[5] N. Luhmann, „Soziale Systeme. Grundriß einer allgemeinen Theorie". Frankfurt am Main, Germany: Suhrkamp, 1987.

[6] H. Haken, "Synergetik," 1983, doi: 10.1007/978-3-642-96775-7.

[7] M. Schulte-Zurhausen, "Organisation," 2013, doi: 10.15358/9783800646906.

[8] H. Schelle, R. Ottmann and A. Pfeiffer, "Project Manager". Nürnberg, Germany:, GPM Deutsche Gesellschaft für Projektmanagement, 2005.

[9] H. Kerzner, “Project Management: A Systems Approach to Planning, Scheduling, and Controlling” 8th ed. Berlin, Germany: Wiley, 2003.
[10] F. Malik, “Systemisches Management, Evolution, Selbstorganisation“, 4th ed. Bern, Switzerland: Haupt Verlag, 2003.
[11] G. Booch G et al., “Objektoriented Analysis and Design”, 3rd ed. Bonn, Germany: Addison-Wesley, 2007.
[12] Eber W 2022, "The Role of Friction in Complex Organisation Networks", Creative Construction eConference 2022, CCC 2022, 09-11 July 2022, Budapest, Hungary..
[13] L. Koskela, “An exploration towards a production theory and its application to construction”. Kivimiehentie, Finland: VTT-Publications, 2000.
[14] J. Zimmermann and W. Eber, “Processes in construction management and real estate development - a systematical approach to the organization of complex projects” in Proc. Creative Construction Conference 2013, Budapest, Hungary, July 6- 9, 2013.
[15] Winch G 2006, "Towards a theory of construction as production by projects" In: Building Research & Information (2006) 34(2), 164-174, https://doi.org/10.1080/09613210500491472..
[16] W. Eber, “Manageability of complex organisational systems – system-theoretical confines of control,” Organization, Technology and Management in Construction: an International Journal, vol. 14, no. 1, pp. 2640–2655, Jan. 2022, doi: 10.2478/otmcj-2022-0009.
[17] L. Koskela, G. Ballard, G. Howell and I. Tommelein, “The foundations of lean construction” in *Design and Construction*: Building in Value”. London, UK: Taylor & Francis, 2002. https://doi.org/10.4324/9780080491080.
[18] *Lean Construction*, VDI 2553, 2019.
[19] K. Beck et al., “The Agile Manifesto” agilemanifesto.org. https://agilemanifesto.org/iso/de/principles.html (accessed Apr. 28, 2021).
[20] K. Schwaber and J. Sutherland, “Scrumguide”, https://scrumguides.org. https://scrumguides.org/docs/scrumguide/v2020/2020-Scrum-Guide-US.pdf (accessed Apr. 28, 2021).
[21] Smith A 1776, "An Inquiry into the Nature and Causes of the Wealth of Nations", vol 1, Nachdruck von 1981, Indianapolis, Indiana, USA, S. 14f., ISBN 0-86597-006-8.
[22] F. Taylor, “The principles of scientific management”. London,UK: Harper & Brothers, 1911.
[23] W. Hoffmann and K. Körkemeyer, “Zum Umgang mit der Komplexität von Bauvorhaben – Ergebnisse einer Expertenbefragung/Handling of Complexity in Construction Projects – Results from an Expert Survey,” Bauingenieur, vol. 93, no. 09, pp. 347–354, 2018, doi: 10.37544/0005-6650-2018-09-47.
[24] A. Picot, H. Dietl and E. Franck, „Organisation - Eine ökonomische Perspektive“, 5. rev. ed. Stuttgart, Germany: Schäffer-Poeschel, 2008.
[25] B. Holmstrom and P. Milgrom, “Multitask Principal–Agent Analyses: Incentive Contracts, Asset Ownership, and Job Design,” The Journal of Law, Economics, and Organization, vol. 7, no. special_issue, pp. 24–52, Jan. 1991, doi: 10.1093/jleo/7.special_issue.24.
[26] E. Ostrom, J. Burger, C. B. Field, R. B. Norgaard, and D. Policansky, “Revisiting the Commons: Local Lessons, Global Challenges,” Science, vol. 284, no. 5412, pp. 278–282, Apr. 1999, doi: 10.1126/science.284.5412.278.
[27] Hardin G 1968, "The Tragedy of the Commons: The population problem has no technical solution; it requires a fundamental extension in morality", Science 13 Dec 1968 Vol 162, Issue 3859 pp. 1243-1248 doi: 10.1126/science.162.3859.1243
[28] W. Eber and J. Zimmermann, “Evaluating and Retrieving Parameters for Optimizing Organizational Structures in Real Estate and Construction Management,” Periodica Polytechnica Architecture, vol. 49, no. 2, pp. 155–164, Nov. 2018, doi: 10.3311/ppar.12709.
[29] W. Eber „Bauprozessmanagement und Immobilienentwicklung - Von den Grundlagen zur Anwendung“ presented at the 13. Kolloquium Investor - Hochschule Bauindustrie 2019, Munich, Germany, München, Jul. 18, 2019.
[30] Selten R 1978, "The chain store paradox". In: Theory and Decision, 9, S. 127-159, 1978 (doi:10.1007/BF00131770).
[31] L. Velthuis, “Das LEN-Modell im Licht des Grundmodells der Principal-Agent-Theorie,” Lineare Erfolgsbeteiligung, pp. 73–100, 1998, doi: 10.1007/978-3-642-52446-2_6.
[32] Lambert R A 2001, "Contracting theory and accounting", Journal of Accounting and Economics, 32, issue 1-3, p. 3-87.

SMALL TO MEDIUM SIZED ENTERPRISES IN CONSTRUCTION INDUSTRY IN OMAN: OPPORTUNITIES, AND CHALLENGES

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Abstract

The development of infrastructure, creation of jobs, and general economic expansion are all facilitated by the construction sector, which is important to Oman's economy. Small- to medium-sized businesses (SMEs) have become key actors in this sector, promoting innovation, employment growth, and local entrepreneurship. To better understand the problems, possibilities, and contributions made by SMEs to the construction industry in Oman, this research offers an outline of the study related to SMEs in Oman. The Sultanate of Oman's government has been fostering a working environment that is encouraging for small and medium-sized businesses for a decade to diversify the sources of income for the country's gross domestic product. Reduced oil dependency, which now stands at 80%, is one of the government's top priorities. As a result, there was a propensity to develop local businesses that were dependent on other forms of commerce. To provide funding for these businesses, the Public Authority for Small and Medium-Sized Enterprises and the AlRaffd Fund were founded. This process has continued for a long time. Although there are fewer firms listed on the market, and the majority of those registered with the General Authority for Small and Medium Enterprises are ineffective businesses, there are still failures. A mixed-methods strategy is used in the research to collect both qualitative and quantitative data. In-depth interviews with key stakeholders, including SME owners, industry experts, and government representatives, are conducted during the qualitative phase to learn more about the distinctive qualities and difficulties experienced by SMEs in the construction industry. In the quantitative phase, questionnaires are sent to a sample of SMEs to collect information on their company practices, financial performance, and growth goals. Initial findings point to numerous important issues. First off, SMEs in the construction sector confront conventional difficulties such restricted access to financing, red tape, and a lack of competent workers. These elements limit their potential for expansion and make it difficult for them to compete with larger businesses. Second, the study points to a number of possibilities that SMEs might seize, including public-private collaborations, government assistance schemes, and technology improvements. By taking advantage of these chances, they may increase their competitiveness and market presence. The survey also reveals the important contributions made by SMEs to the building sector. SMEs, although having minimal resources, are essential for creating jobs, especially for local areas. Through their flexibility, adaptability, and openness to adopt cutting-edge building techniques, they also promote innovation. In addition, SMEs support local economic growth by encouraging entrepreneurship and fostering the expansion of auxiliary sectors.

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Keywords: small enterprise, medium enterprise, construction industry, construction challenges, construction opportunities

1. Background

Expansion of the various infrastructure projects of the country, generation of jobs, and general advancement are all facilitated by the construction sector in Oman, which is crucial to the nation's economic prosperity. Small- to medium-sized businesses (SMEs) have become significant actors in this industry, promoting innovation, local entrepreneurship, and economic diversity. For SMEs to be successful and increase their contributions to Oman's economy, it is essential to understand both the opportunities and challenges they encounter in the construction sector. SME growth and sustainability in the construction sector are impacted by a unique combination of possibilities and difficulties. To create strategies and policies that promote their development, it is crucial to investigate these aspects. To increase their competitiveness and increase their market share, SMEs might take use of public-private partnerships, government assistance programs, technical breakthroughs, and specialized markets. On the other hand, they face difficulties such restricted access to financing, red tape, a lack of competent workers, and strong competition from larger enterprises.

Alhasmi [1], the Board of Directors of the Public Agency for Small and Medium Enterprises Creation (Riyada) has reported that more than 10% of the tenders and purchases should be allocated to small and medium enterprises registered in Riyada as part of the support for entrepreneurship initiatives and to provide them with business opportunities. Whereas the number of small and medium-sized companies registered under "Riyada" is only 2.5%. This is very low percentage of what those authorities expected. Most data, according to Kumar [2], show that a portion of all yearly contracts are given to small and medium-sized businesses. However, the numbers show that these contracts are in the area of supply and services and have nothing to do with building, which is contrary to the data provided by the General Authority. This shows that the industry lacks passion and concentration, in contrast to other industries that design an exciting workplace and rules that suit their needs. The government has launched numerous initiatives in recent years to support the expansion of small and medium-sized businesses throughout the Sultanate of Oman. But these have been hampered by a lack of coordination that is incompatible with the success of an organized approach and by numerous policy and feasibility deficits [3]. This research investigates the status of SMEs in Oman's construction sector, illuminating the possibilities they may take advantage of and the difficulties they must face. This research aims to give a deeper knowledge of the distinctive dynamics and features of SMEs in Oman construction sector by performing a thorough study using a mixed-methods approach, integrating qualitative and quantitative data gathering approaches.

2. Research problem and significance

Small and medium-sized businesses (SMEs) are crucial to the construction sector's ability to innovate, expand, and create jobs in Oman. However, SMEs in the construction sector confront several difficulties that limit their ability to expand and make a general contribution to the industry. It is essential to recognize and solve the issues SMEs face to ensure their sustained growth and optimize their beneficial effects on Oman's building sector. The main problem lies in the opportunities and challenges facing small and medium enterprises in the construction sector. Sultanate of Oman is one of the countries that is based on the continuity of developing the infrastructure and constructs many construction projects. Therefore, the chances are high for small enterprises to obtain their share of these projects, and here emerges one of the reasons that the research will focus on, which is the imposition of strict laws and financial penalties on everyone who does not assign 10% of the contract value to small and medium enterprises. The issue statement includes the requirement to identify the primary barriers impeding the development of SMEs in the construction industry. Policymakers, industry participants, and SME owners may collaborate to discover practical answers to these problems by being aware of them. Additionally, analysing how these issues affect SMEs' development, competitiveness, and sustainability will assist in developing focused strategies and policies that support their growth and increase their contributions to Oman's construction sector.

3. Literature Review

In literature [4]–[7], it is emphasized how essential SMEs serve the construction sector, especially in developing nations like Oman. SMEs support local entrepreneurship, economic diversity, and job development. They are commended for their adaptability, creativity, and capacity to satisfy changing market demands. The literature has identified several issues that SMEs in the construction sector face. The difficulty SMEs have in acquiring loans from traditional sources owing to perceived risk and a lack of collateral is a typical topic of worry [8]. SME operations and project execution are also hampered by administrative obstacles including difficult rules and drawn-out administrative processes. In addition, SMEs struggle with a lack of competent personnel, making it difficult to recruit and retain qualified professionals. Literatures identifies plenty of opportunities that SMEs may take advantage of to increase their competitiveness. Based on the review, construction-related SMEs provide a substantial contribution to job creation, especially for local areas. Their adaptability and readiness to adopt new technology encourage innovation and enhance business procedures. By encouraging entrepreneurship and fostering expansion in auxiliary sectors, SMEs also support regional economic growth [4].

4. Research methodology

A mixed-methods approach was used in the research technique for this study to offer an in-depth understanding of the challenges faced by small and medium-sized firms (SMEs) in the Omani construction sector. In this study, data were gathered using a survey questionnaire from tens of SME owners or managers in Oman's construction sector using a quantitative and qualitative research approach. Due to the unavailability of a complete database of SMEs in the construction industry in Oman, snowball sampling was employed to select respondents.

A representative sample of Oman's SMEs in the construction sector received a structured questionnaire. The survey collected quantitative information on number of different topics related to the challenges and potential opportunities of supporting SMEs in Oman construction industry. To produce descriptive and inferential statistics, the quantitative data has been evaluated statistically. In addition, qualitative data have been collected through in-depth interviews and focus groups. Owners of SMEs, industry professionals, public authorities, and other pertinent stakeholders were included in the sample. These in-depth qualitative interviews on the issues encountered by SMEs documented participant opinions, experiences, and insights. Thematic analysis method is used to examine the qualitative data in order to find recurrent themes and patterns. Table 1 shows the sample size, and the participants sectors as well.

To give a thorough examination of the difficulties faced by SMEs in the construction sector, qualitative and quantitative data were individually and jointly assessed. To find important themes and patterns, the qualitative data was evaluated using thematic coding and interpretation. To study the relationships between variables and offer numerical insights, the quantitative data has been evaluated using statistical techniques such frequency analysis, correlation analysis, and regression analysis.

Table 1: Sample size and participants' sectors

Sector	Participants	%
Government sector	44	45.4
Private sector	53	54.6
Total	**97**	**100**

5. SMEs challenges

The various obstacles that SMEs in Oman's construction sector face have been highlighted in multiple research studies. Lack of access to capital, governmental rules and regulations, a skilled labor shortage, the high cost of raw materials, and inadequate technical expertise are a few of the current issues. Intense competition, poor enterprises margins, late payments, and cash flow problems present further difficulties. SMEs in the construction sector sometimes struggle to get sufficient finance [9]. Construction projects may be viewed as high-risk by conventional financiers, which would limit the amount of finance available to SMEs. The situation is further complicated by the absence of collateral and the cyclical nature of the construction sector, making it challenging for SMEs to get financing for working capital, company development, and investment in machinery and technology. When dealing with regulatory regulations, getting permits, licenses, and approvals from numerous government authorities, SMEs encounter bureaucratic hurdles. Long administrative procedures, intricate rules, and ambiguous guidelines can cause project delays, raise expenses, and generally reduce the effectiveness of SME operations.

In addition, there is a lack of trained workers in Oman's construction sector, including engineers, architects, project managers, and specialist craftspeople. Due to fierce competition from bigger businesses, a lack of resources for paying competitive compensation, and the attractiveness of job prospects abroad, SMEs frequently struggle to attract and retain competent experts [10]. The quality and timely completion of construction projects may suffer from a lack of competent personnel, which might hinder the competitiveness and expansion of SMEs. SMEs in the construction sector compete strongly against bigger, larger companies that have more financial resources, a better reputation, and long-standing connections with clients and suppliers [7]. Since big contracts and projects are often given to larger companies based on their track record and capability, SMEs sometimes find it difficult to compete for them. The development potential and market share of SMEs in the construction industry may be constrained by this unfavourable playing field [6]. Based on the conducted survey, Table 2 shows the factors affecting in SMEs contribution in Oman construction industry. Most of participants confirmed that major reason is because of employer trust in SMEs then the contract general terms and conditions.

Table 2: Factors affecting the contribution of SMEs in Oman construction industry

Factors	Strongly disagree	Disagree	Natural	Agree	Strongly agree
The Employer does not trust SMEs	1	4	20	28	44
The general terms and conditions of the tenders exceed the capabilities of SMEs	1	8	33	37	18
Technical criteria exceed the capabilities of SMEs	-	12	40	31	14
SMEs submission of the tender document does not comply with the employer aspirations	3	17	42	21	14
Other	7	8	57	18	6

For SMEs, the construction industry's fast technological development presents both possibilities and difficulties. While technology may increase productivity, streamline operations, and improve project management, SMEs may find it difficult to afford the costs associated with integrating new technologies [11]. Lack of knowledge, a lack of financial resources, and an aversion to change might prevent SMEs from fully using the advantages of technology improvements in the construction industry. Risks and uncertainties are a natural part of every construction project, and these might include things like changing material pricing, project completion delays, and unanticipated difficulties. Small and medium-sized businesses (SMEs) may find it more difficult to properly manage and mitigate these risks, which might have an influence on project profitability and overall business performance [2]. SMEs in Oman's construction sector to thrive and flourish sustainably, it is imperative that these issues be resolved. By putting supportive measures in place, offering targeted financial assistance, streamlining regulatory procedures, promoting skills development programs, and encouraging cooperation between SMEs and larger industry players, policymakers, industry associations, financial institutions, and SME owners can work together to overcome these obstacles. By resolving these issues, SMEs may improve their competitiveness, broaden their market reach, and considerably boost the growth of Oman's construction sector [12]. For Oman construction industry, Table 3 shows the major challenges and barriers that faces SMEs and need immediate intervention to sort it out by all stakeholders. Lake of knowledge, limited capacity and financial issues are the major challenges for SMEs in Oman.

Table 3:SMEs challenges and barriers in Oman construciton industry

Factors	Strongly disagree	Disagree	Natural	Agree	Strongly agree
Lack of business necessary knowledge.	-	7	25	47	18
Lack of financial access and guarantees provided to funding institutions.	1	5	34	46	11
Hidden trade and government tax because of lack of regulation and administrative burdens.	-	7	45	37	8
Limited capacity to grow.	1	9	23	39	25
Lack of will and method from employees about the incorporation of modern technology in business.	3	7	52	27	8
Other	1	9	60	20	7

According to Kolosz'ar [13], one of the crucial elements for a competitive economy is the development of a robust, globally competitive SME sector. SMEs are experiencing poor management. Kolosz'ar [13] conducted a thorough examination and analysis of the lean approach-using SMEs operating in Hungary's industrial sector. Small- and medium-sized business participants, primarily CEOs and managers from Hungary's manufacturing sector, undertook the study. It first demonstrates the low amount of lean usage among Hungarian SMEs. Additionally, the most crucial fundamental element in this sector is client orientation. Dana [9] and Pauceanu [10] states that GCC SMEs businesses have issues in getting financing from the commercial banks. Risk capital, private equity, and angel-investor equities are examples of alternative investments. These include measures made by the European Union that permit India's non-institutionalized involvement in the need for SMEs to invest in stock exchanges and that encourage public sector banks to provide promissory stocks to SMEs in the region. It might be difficult for the GCC to promote private equity in the SME sector. To reduce this risk, GCC governments should implement initiatives to assist SMEs that struggle to draw in investors from private equity.

6. SMEs opportunities in Oman construction industry

Several actions have been made by Omani government authorities and foreign organizations to encourage the expansion and development of SMEs in the nation. To close the funding gap and offer mentorship, training, and support services for SMEs, programs including the Al Raffd Fund, Riyada, the Public Authority for SME Development, and the National Business Centre have been formed. Additionally, the government has implemented regulations to improve SME possibilities in public procurement and to simplify regulatory procedures [11]. The effects of SMEs on the national economy in the Omani construction sector have been studied by researchers. Al-Balushi and Bagumire [12] emphasized the considerable contribution made by SMEs to Oman's GDP through the creation of jobs and the reduction of poverty. They also stressed the sector's significance in promoting regional growth, innovation, and productivity. Oman government has many resources and support to acknowledge the worth of SMEs. The directorate's role is to coordinate with government departments, give entrepreneurs with structured information and training, and identify alternative financing sources to handle their financial issues. Small and medium-sized enterprises (SMEs) are crucial for the development of Oman's construction sector. Based on the conducted interviews with various stakeholders, following are some of the potentials for SMEs in Oman's construction sector:

- The Omani government has introduced several programs to support the expansion and sustainability of SMEs in the nation. The Al Raffd Fund, Riyada, Public Authority for SME Development, and National Business Centre are just a few of the initiatives that provide access to funding, coaching, training, and other crucial support services.

- The government of Oman has put in place procurement procedures that give SMEs preference for building contracts. Due to these rules, SMEs now have more opportunity to participate in public infrastructure projects and grow their companies.

- The government of Oman is making significant investments in infrastructure development, giving SMEs the chance to participate in these large-scale projects. In addition to roads, hospitals, airports, and ports, these developments also include housing developments and tourist attractions.

- Adopting contemporary building technology may present SMEs with fresh chances to improve output, effectiveness, and efficiency. Using BIM (Building Information Modeling), off-site manufacturing methods, and other cutting-edge tools can assist SMEs in streamlining operations and lowering operating expenses.

- SMEs can work together and establish collaborations with larger construction enterprises and foreign businesses. These collaborations may create chances for information sharing, collaborative project bidding, and access to bigger construction contracts, facilitating SME expansion within the sector.

- Opportunities for SMEs to specialize in green construction methods are presented by the push for sustainable development in Oman and the escalating environmental concerns. SMEs may meet the rising demand for sustainable building approaches by implementing eco-friendly materials and energy-saving techniques.

- For SMEs, the lack of trained workers in Oman's construction sector presents an opportunity to concentrate on training and skills development initiatives. SMEs will be better able to deliver high-quality services within the sector if the skills gap is closed.

7. Conclusion

In summary, this study describes the main obstacles and possibilities that SMEs working in Oman's construction sector must overcome. Fostering the expansion of SMEs through specialized policies and assistance programs may contribute to economic growth, job opportunities, and innovation within the construction industry. The efficiency of government assistance initiatives and the potential advantages of partnerships between SMEs and bigger construction companies both require additional study. The research has, however, also identified a wide range of prospects for SMEs in Oman's construction sector. Infrastructure development, affordable housing, travel and hospitality efforts, industrial and commercial facilities, rehabilitation and retrofitting, government programs, green construction and sustainability techniques, and technology adoption are some of the options that are available. SME's may build their companies, increase their market presence, and aid in the economic growth of Oman by utilizing these chances. Small and medium-sized businesses (SMEs) must overcome the difficulties highlighted in order to flourish in this cutthroat market. To achieve this, they must apply for funding from specific programs, increase their competitiveness through specialized services, adopt sustainable practices, embrace technology, and take advantage of government initiatives. For SMEs to succeed, collaboration with bigger construction firms, networking with industry players, and ongoing professional growth are also essential. The study provided important light on the potential of SMEs in Oman's construction sector. It provides a framework for more research and the development of policies to aid in and accelerate the expansion of SMEs. Oman may provide an enabling environment for SMEs in the construction sector by putting in place helpful measures such simpler access to finance, regulatory simplification, capacity-building programs, and market information distribution.

References

[1] J. Alhashmi, “Over 40,000 companies registered as SMEs in Oman,” *Times News Service*, 2020. https://timesofoman.com/article/1899218/oman/over-40000-companies-registered-as-smes-in-oman-riyada

[2] A. K. Sahu, R. K. Padhy, D. Das, and A. Gautam, “Improving financial and environmental performance through MFCA: A SME case study,” *J. Clean. Prod.*, vol. 279, p. 123751, 2021.

[3] M. A. Alqassabi, “Insights on Sustainability of Small and Medium Enterprises in Oman: a Conceptual Framework,” *Int. J. Econ. Financ. Issues*, vol. 10, no. 1, pp. 209–218, 2020, doi: 10.32479/ijefi.9063.

[4] I. Apulu and A. Latham, “Benefits of information and communication technology in small and medium sized enterprises: a case study of a Nigerian SME,” *Proc. 15th Annu. Conf. UK Acad. Inf. Syst.*, vol. 1, pp. 23–24, 2010.

[5] C. Mac an Bhaird, “Resourcing Small and Medium Sized Enterprises,” *Resourcing Small Mediu. Sized Enterp. A Financ. Growth Life Cycle Approach*, no. 332, pp. 23–43, 2010, [Online]. Available: http://link.springer.com/10.1007/978-3-7908-2399-8

[6] Sileshi Talegeta, “Innovation and Barriers to Innovation: Small and Medium Enterprises in Addis Ababa,” *J. Small Bus. Entrep. Dev.*, vol. 2, no. October, 2014, [Online]. Available: https://www.researchgate.net/profile/Sileshi-Talegeta/publication/349142456_Innovation_and_Barriers_to_Innovation_Small_and_Medium_Enterprises_in_Addis_Ababa/links/60f530690859317dbdf20f8f/Innovation-and-Barriers-to-Innovation-Small-and-Medium-Enterprises

[7] H. T. T. Tran, “Challenges of Small and Medium-Sized Enterprises (SMEs) In Vietnam during the Process of Integration into the ASEAN Economic Community (AEC),” *Int. J. Account. Financ. Report.*, vol. 5, no. 2, p. 133, 2015, doi: 10.5296/ijafr.v5i2.8298.

[8] A. Al-Maskari, M. Al-Maskari, M. Alqanoobi, and S. Kunjumuhammed, “Internal and external obstacles facing medium and large enterprises in Rusayl Industrial Estates in the Sultanate of Oman,” *J. Glob. Entrep. Res.*, vol. 9, no. 1, pp. 1–20, 2019, doi: 10.1186/s40497-018-0125-3.

[9] A. Wubishet Ayele and A. B. Derseh, “Challenges that Hinder the Sustainability of Small and Medium Scale Enterprises in East Gojjam Zone, Northern Ethiopia,” *Int. J. Dev. Res.*, vol. 10, no. 07, pp. 37926–37934, 2020, doi: 10.37118/ijdr.19201.07.2020.

[10] Y. Wang, “What are the biggest obstacles to growth of SMEs in developing countries? – An empirical evidence from an enterprise survey,” *Borsa Istanbul Rev.*, vol. 16, no. 3, pp. 167–176, 2016, doi: 10.1016/j.bir.2016.06.001.

[11] D. Makondo, “Application of Lean Principles in Small and Medium Enterprises: The Case of the Construction Industry in the Ekurhuleni Metropolitan Area,” vol. 0002, no. August, 2017.

[12] O. Isokratous, “What are the Barriers that Prevent the Development Process of Small and Medium Construction Companies in Greece.” 2006.

[13] L. Koloszár, “Opportunities of Lean thinking in improving the competitiveness of the Hungarian SME sector,” *Manag. Prod. Eng. Rev.*, 2018.

[14] L. Dana, R. Palalic, and V. Ramadani, *Entrepreneurship in the Gulf cooperation council region: Evolution and future perspectives*. World Scientific, 2021.

[15] M. Pauceanu, *Entrepreneurship in the Gulf Cooperation Council: Guidelines for Starting and Managing Businesses*. Academic Press, 2016.

[16] S. M. Al-Lamki, “Omanization: A three tier strategic framework for human resource management and training in the Sultanate of Oman.,” *J. Comp. Int. Manag.*, vol. 3, no. 1, pp. 55–75, 2000.

[17] B. H. S. Al Bulushi and S. Bagum, “Growth strategies of sme in Oman-Issues and challenges,” *Int. J. Small Bus. Entrep. Res.*, vol. 5, no. 2, pp. 21–61, 2017.

SENTIMENT ANALYSIS MODEL FOR PUBLIC CONSTRUCTION PROJECTS USING KOBERT

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Abstract

The development of real-time communication technology has accelerated and enlarged conflict propagation, resulting in social conflicts in modern society. Social conflict significantly impacts the execution of a public construction project. Conflict of interest between stakeholders may cause construction delays and even cease the project. Against this backdrop, the authors aim to develop a proactive conflict management system based on Natural Language Processing (NLP) for public construction projects. As a point of departure, this paper introduces a social acceptance assessment model using Social Network Service (SNS) data. The authors employ Korean Bidirectional Encoder Representations from Transformers (KoBERT) for the text model development. The proposed model has two main functions. One is to filter out irrelevant text with the execution of a construction project. The other is to measure the degree of agreement on an ongoing construction project as social acceptability considering the semantic context of input text. Then, the keyword analysis is done to draw out the main thesis of social conflicts in public construction projects. An illustrative case application is done to validate the model's applicability and to illustrate how sentiment analysis and keyword analysis be done. The proposed model is expected to detect potential social conflict signals through real-time monitoring, enabling the proactive reaction to prevent social conflicts during the execution of public construction projects.

Keywords: conflict management, public construction project, sentiment analysis, keyword analysis.

1. Introduction

1.1. Research background

The development of real-time communication technology has accelerated and enlarged conflict propagation. People can share information and communicate with each other without any time or place constraints. Therefore, there are lots of surfaced social conflicts in modern society. Social conflict significantly impacts the execution of a public construction project. Conflicts may cause construction delays, increased costs, or even termination of the project [1]. Since conflict keeps increasing in the construction industry, and conflicts are becoming inevitable, conflicts should be managed systematically to successfully implement public construction projects. Several studies have been conducted in line with problems that tried to manage conflict, but they mainly focused on internal conflict [2]. Moreover, previous studies have analyzed conflict management strategies on a conflict-by-conflict basis. However, due to the nature of the construction sector, no comprehensive project-level conflict management system has been proposed to the best of our knowledge. Therefore, this study aims to develop a proactive conflict management system using Natural Language Processing (NLP) to deal with social conflict problems for public construction projects.

1.2. Research framework

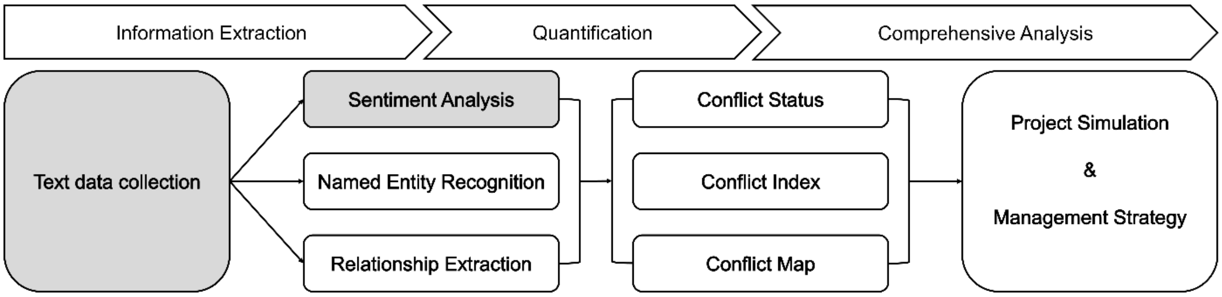

Fig. 1. Proactive conflict management system

Fig. 1 shows the overall structure of conflict management system. The proposed system enables conflict management throughout the whole project lifecycle from preventing possible conflict to resolving occurred conflict. This collects text data and extracts information related to construction conflict using NLP. Based on the extracted information, the model assesses where the conflict is in its current phase, suggests possible scenarios which are likely to play out, and establishes corresponding management strategies

This paper presents the development of a model for extracting sentimental information that corresponds to the part marked by grey boxes within the entire system. This model serves to extract a piece of information to drive the entire system. Through the model, sentiment information is extracted and used to assess the social acceptability score. The social acceptability score is an index regarding conflict status and conflict that illustrates the citizen's acceptance toward a public construction project. The deduced score is used as a variable to assess the current state of conflict and helps us get an insight into how the conflict is going to be developed.

2. Literature Review

2.1. Conflict management in construction sector

Previous studies related to the conflict in construction focused on investigating the nature of the conflict. Jaffar et al. [1] provides an overview of the factors that contribute to conflict in construction projects, and identifies three types of conflict factors: behavioral, contractual, and technical driven conflicts. This paper aimed to serve a guideline for effective conflict management based on identified conflict factor types. Jehn et al. [3] examined three types of conflict (task, relationship, and process) and four dimensions of conflict (emotions, norms, resolution efficacy, and importance). Moreover, this study investigated effects of conflict types and dimensions on productivity and viability, and concluded that all types of conflict decreased productivity and viability. Brockman [4] defined triggers and consequences of interpersonal conflict on a construction site and their consecutive financial costs based on interview toward construction industry personnel. This study concluded that to keep the cost of conflict at a minimum, resolving conflict closest to the trigger event in both space and time is the most effective way, and emphasized the importance of prevention and early intervention of conflict. Lee et al. [2] suggested a social conflict management framework based on causes, impacts, and resolutions of conflicts through case studies from Korean megaprojects. Moreover, five conflict scenario types were derived, and they defined root causes, pathways of conflict propagation, and characteristics of derived conflict scenarios. These approaches tried to address conflict via analysis of conflict itself. They tried to get a better understanding of the conflicts, and thus gain keys to conflict management.

Meanwhile, some researchers regarded the conflict as a stakeholder management problem. According to Nguyen et al. [5], there were 4 themes related to stakeholder management: stakeholder analysis, stakeholder influence, stakeholder management strategies, and stakeholder engagement. This study showed that stakeholder analysis and stakeholder engagement were the main topics of stakeholder management approach and concluded that these are effective in addressing the complexity of conflicts.

Li et al. [6] noted that stakeholders' engagement to project decision making can address issues such as failing to meet the concerns and expectations of stakeholders which result in many project failures. Along this line, this study suggested a means of evaluating the effectiveness of public participation through the measurement of stakeholder satisfaction considering that stakeholder participation affects construction conflict significantly, adopting a fuzzy approach. On the other hand, Olander [7] analyzed a stakeholder impact index as a part of stakeholder analysis. The proposed index was introduced to reveal the impact and probability of stakeholders' influence to effectively manage stakeholders and mainly focused on analyzing characteristics of stakeholders rather than analyzing their engagement into the project.

Along with the development of digital technology, tangible information related to the conflict exists in the form of documents represented by reports, news, and SNS. Previous studies have focused on qualitative research such as case study or survey. However, there was little study that focused on quantitative analysis based on text analytics that can assure the objectivity of the study.

2.2. Text-based research in construction sector

NLP technology, which enables human language to be understandable by machines, has developed rapidly and research using NLP technology has been actively conducted in the construction domain [8]. There are potential advancements using NLP in construction engineering and management for that abundant data is valid by digital transformation. Previous studies in construction have applied NLP to solve practical problems such as using safety documents, bidding, and contract documents. SNS data is also one of promising sources. Tang et al. [9] compared construction industry in China and the United States by using network link analysis and NLP tools. This study used SNS data for analysis and revealed that the two countries shared similar trends, but the biggest difference was that the US focused more on safety and energy, while China focused more on infrastructure. Zhou et al. [10] proposed an analytical framework to extract public opinion using LDA(Latent Dirichlet Allocation) and rule-based sentiment analysis. Milestone events and special events were extracted through topic modelling, and concerns revealed through topic modelling were reflected in increasing negative sentiment toward the project.

Conflict during construction projects is related not only to internal but also to external stakeholders such as local residents, environmental oragnizations, etc. Thus, recognizing external stakeholders' needs and requirements is essential to manage conflict. The authors determined that SNS is one of the promising sources for identifying how external stakeholders, who are end-users of the public infrastructure, perceive the planned or ongoing projects.

3. Methodology

3.1. Sentiment analysis

Sentiment analysis is a method of extracting sentimental information presented in a given text and classifying the text into predefined categories based on the context of each text. Sentiment analysis is also known as opinion analysis because of its ability to detect opinions toward products. There are several ways to perform sentiment analysis such as lexicon-based approach, ML-based approach, or hybrid approach. Lexicon-based approach does not require training data, but highly domain oriented. To overcome its limitation, ML-based approach has been developed. ML-based supervised learning methods are more commonly used due to their accurate results, but they need to be trained before application. Hybrid approach combines these two methods [11]. After the introduction of Bidirectional Encoder Representations from Transformers (BERT) which employed the self-attention mechanism, ML-based approach has shown superior performance compared to other methods. Therefore, this study performed the sentiment analysis based on Korean BERT (KoBERT) to analyze sentiment of text written in Korean. The extracted sentiment is analyzed in the form of ratios and utilized to assess the social acceptance of projects. Moreover, algorithms that are used to perform sentiment analysis can be applied to general text classification tasks because the essence of sentiment analysis is text classification.

3.2. Pretrained language model

3.2.1. BERT

BERT is a pretrained language model based on the self-attention mechanism which can access the global information of the text. The model is composed of 12 transformer encoder blocks, 768 hidden-size word embeddings, and 12 self-attention heads. Utilizing the pre-trained BERT model and fine-tuning all the parameters using training data allows good performance on downstream task such as classification. Fine-tuning method enabled inexpensive application to downstream tasks without any explicit training data, while guaranteeing fine performance [12].

To apply BERT to classification tasks such as sentiment analysis, input data is represented by a sequence of tokens. Tokenizer is used to tokenize the input data, and convert it into a sequence of tokens. BERT applied WordPiece Tokenizer which is a subword tokenization technique that segments words into smaller units and assigns a unique token to each subword unit. Each token is embedded by the sum of token embedding, segment embedding, and position embedding. At the front of the token embedding sequence, [CLS] token is added as special token embedding for classification tasks that implicate the whole information of the sequence. [CLS] token is mainly used for document-level or sentence-level classification tasks.

3.2.2. KoBERT

Google AI Language researchers introduced several language models including BERT base multilingual cased which is for multilingual texts, but it showed relatively poor performance with texts written in Korean compared to English. SKTBrain developed Korean BERT (KoBERT) in the purpose of overcoming the poor performance of processing Korean texts using BERT base multilingual cased. The model's architecture of BERT and KoBERT is the same, but KoBERT is trained with a corpus of millions of Korean sentences collected from Korean Wikipedia and News instead of BooksCorpus and English Wikipedia which BERT used. Due to the nature of Korean as an agglutinative language, KoBERT developed its own unique tokenizer based on SentencePiece method to reflect the nature of Korean as an agglutinative language. This study employed KoBERT as a basis pretrained language model and fine-tuned it for the sentiment analysis task.

3.3. KeyBERT

KeyBERT is a keyword extraction technique that uses embeddings generated by BERT to extract words that are most similar to a document [13]. Document embeddings and word embeddings are extracted by BERT, and the words that are most similar to the text are selected. Various methods such as cosine-similarity, max sum similarity, and maximal marginal relevance are used to calculate the similarity of the word and the text. Cosine-similarity allows obtained keywords to be consistent, while using max sum similarity or maximal marginal relevance allows for getting diverse keywords. In this study, KeyBERT is applied to define the main topic and subject of the input text by extracting keywords that are representative to a document. To identify topics running through a text, we decided to apply cosine-similarity which can extract consistent keywords.

4. Experiment

4.1. Data collection

4.1.1. Web crawling

This study used SNS text data to analyze sentiment toward public construction projects. The authors crawled SNS texts related to four representative public construction projects which had severe conflicts in Korea (Table 1).

Table 1. Basic information of selected projects

Project Name	Project Type	Conflict Factors. [2]
Gadeok Island Airport	Airport	Environmental concerns
		Location selection issue
Miryang Transmission Tower	Transmission Tower	Environmental concerns
		Enforcement of project
Jeju Naval Base	Military Base	Environmental concerns
		Damage to properties
4 Major Rivers Project	Infrastructure (Barrage)	Environmental concerns
		Opaque project objective

This study collected the Twitter and Instagram text data posted over the past five years (2017- 2022). As a result, 1,265 Instagram postings and 1,906 Twitter tweets were collected. Then, the authors labelled each text into four classes (positive, neutral, negative, and irrelevant). Table 2 presents an overview of the labelled dataset.

Table 2. Overview of datasets

Data Source	Positive	Neutral	Negative	Irrelevant	Total
Instagram	116	112	344	693	1,265
Twitter	267	290	1,091	258	1,906
Total	383	402	1,435	951	3,171

After labelling, the dataset was split randomly into a training dataset and a test dataset at a ratio of 8:2. When splitting the dataset, the class distribution was taken into account to deal with unbalanced data distribution.

4.1.2. Text preprocessing

Text data collected by web crawling contains various components that can negatively affect the model performance. While maintaining the original meaning of the data, text cleaning was done by removing words such as “RT @”, “Retweeted”, “RT”, HTML characters, garbage words, and recurring special characters.

4.2. Sentiment analysis

In this paper, sentiment analysis is performed through two functions: validity classification and polarity classification. Because the purpose of the sentiment analysis is to detect sentiment toward project related to conflict issues, input text first passes through the validity classification model to sort construction-related text. After that, the sorted text passes through the polarity classification model which classifies the sentiment of the input text.

After passing through the KoBERT model, a fully connected layer is added to the last layer of the position of [CLS] token embeddings for classification. The output of this layer contains scores for each class, and the model predicts the class of input text by selecting the class with the highest score. For the loss function, we applied the cross-entropy loss function which is widely used for multiple classification problems. The hyperparameters of the models were set as follows; a learning rate of 5e-5; a dropout probability of 0; a batch size of 64. For optimizing, we adopted AdamW optimizer.

4.3. Keyword analysis

To define the main topic and subject of the argument, this study performed the keyword analysis. The top 3 relevant keywords were extracted from each input text by deducing words that are most similar to the text based on cosine similarity. Frequency analysis was then performed to identify the main subject of the argument during the given period. By extracting main keywords monthly, the authors identified changes and flows of arguments and interpreted them in conjunction with the sentiment analysis results.

5. Result

5.1. Evaluation metrics

In this research, the performance of the model is measured based on F1 score. Because the dataset is imbalanced, accuracy can be a misleading metric. On the other hand, F1 score is better suited for imbalanced datasets because it gives more weight to class with fewer samples. In this study, the micro average of F1 score is calculated to account for data imbalance.

5.2. Experiment result

The average F1 scores of the validity classification and polarity classification are 87.1% and 82.9% respectively. The performance of the validity classification model was better than the performance of the polarity classification model. The reasons for this result are as follows. First, sentiment toward the construction project is expressed in various ways. For example, some text shows negative sentiment toward the project by direct wordings such as ‘Completion of Gadeok Airport on Time, we will make it happen’. On the other hand, some text shows negative sentiment toward the project in indirect ways such as showing negative sentiment toward key stakeholders promoting the project, using antonyms, and supporting alternative options for implementing the project. This ambiguity in the way of voicing the opinion affected the performance of the model. Second, the balance of classes is imbalanced. Positive and neutral text data is relatively fewer than negative text data. Negative text data takes up a large portion of the overall dataset. This imbalanced dataset affected the training of the sentiment analysis model.

5.3. Case application

This study performed a real case application to validate the proposed model and illustrate how sentiment analysis and keyword analysis can be used. The authors selected the Ilsan bridge project as a real case that suffered from conflict related to the facility price issue. Conflict around this project started in 2021 and is still ongoing. Key events of the conflict surrounding this project, and a timeline of the conflict are presented on Fig. 2. On September, 2021, the conflict was triggered by the governor who cited the facility’s executive tolls as a problem and announced that it would be made free. On November, 2021, collectivization of the facility was done by the local government, but an injunction was granted by the court resulting in tolls remaining the same. On November, 2022, the court ruled that the local government’s actions were in violation of the rules.

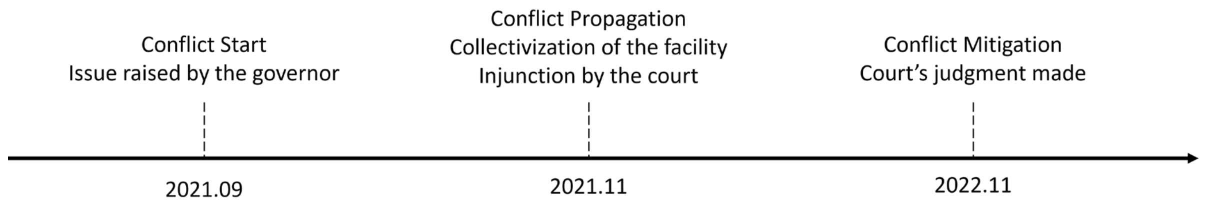

Fig. 2. Conflict timeline

The total of 3,215 tweets were collected from 2021 to the present. After conducting the validity classification, 2,714 tweets were separated out to be the relevant data. Irrelevant tweets were mostly daily tweets or advertisements. Toward the relevant tweets, polarity classification was conducted, and result is given on Fig. 3.

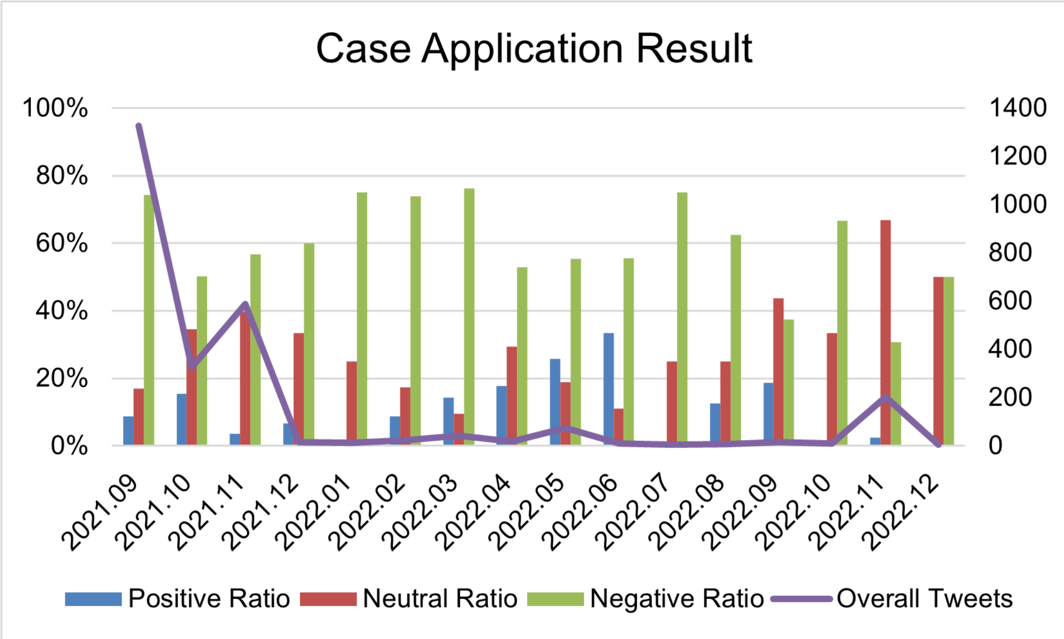

Fig. 3. Case application result

Collectively, 63.19% of the tweets was determined to be negative, so negative opinions were dominant throughout the all period. We observed how key events affect public opinion through sentiment analysis results over time. On September, 2021, after the governor's announcement, many tweets were posted, and 75% of the tweets posted in this period were negative which is more than normal. It was a time that conflict started, and the suddenness of the governor's announcement brought out a lot of dissenting opinions. On November, 2021, negative tweets have decreased to 56.71% which is 20% lower than on September, 2021. Also, both positive/negative tweets decreased, and neutral tweets increased. Because of the intervention of the law, mitigation of the conflict was observed. On November, 2022, after the court's judgment, negative tweets decreased to 30.69% which is 26% lower than that of November, 2021. Even though conflict can be reignited by raising of issue again, the court's ruling had the effect of quelling conflict and reducing dissent.

Keyword analysis by period was conducted to verify whether the keyword analysis captures the main thesis of each analysis period: September, 2021, November, 2021, November, 2022, respectively. The top 3 most commonly used keywords on September, 2021 were "Ilsan bridge", "National Pension System (NPS)", and "Jaemyung Lee" which are the main parties of the conflict. Moreover, keywords such as "toll fee" or "Gyeonggi province" were also detected frequently which implicate a point of the conflict and the main party involved. The top 3 most commonly used keywords on November, 2021 were "court", "Jaemyung Lee", "Ilsan bridge". Extracted keywords were in line with the previous result, but the new keywords "court" replaced "NPS" which implies that legal intervention was made. Considering the result of the sentiment analysis, legal intervention decreased the number of pros and con opinions and moved to more neutral opinions. It implies that the intervention of the law mitigates the controversy. Moreover, after the court's intervention, a number of tweets posted decreased, which means that surfaced conflict has been mitigated. Lastly, the top 3 most commonly used keywords on November, 2022 were "losing a suit", "Gyeonggi province", "Ilsan bridge" which implies that the court's ruling was made. The term "losing a suit" and "Gyeonggi province" implies that Gyeonggi province lose a suit. Considering the result of the sentiment analysis, negative opinion severely decreased, because the court's decision was at odds with the dissenting opinion. Based on the analysis, we concluded that keyword analysis successfully drew out the main thesis.

6. Conclusion

This study proposed the sentiment analysis model using KoBERT to analyze sentiment toward public construction projects. To validate the proposed model, this study conducted a case application. The authors observed how key events affect the public opinion revealed by sentiment and keyword analysis. The result of the experiment verified that fine-tuned sentiment classification model is applicable to unstructured text from SNS in the construction domain. Collecting and utilizing real-time information is crucial to preventing and analyzing conflicts, but post-mortem based conflict analysis cannot address to real-time information. This study revealed that NLP tools can identify real-time conflict information on SNS and automate the information collection process. However, since this paper presented a pilot sentiment and keyword analysis model only based on the original KoBERT, the proposed model showed somewhat insufficient performance for practical application. In future research, the authors will improve the performance of the model by applying aspect-based sentiment analysis and rebuilding the model architecture.

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References

[1] N. Jaffar, A. H. A. Tharim, and M. N. Shuib, “Factors of Conflict in Construction Industry: A Literature Review,” *Procedia Engineer*, vol. 20, pp. 193–202, 2011, doi: 10.1016/j.proeng.2011.11.156.
[2] C. Lee, J. W. Won, W. Jang, W. Jung, S. H. Han, and Y. H. Kwak, “Social conflict management framework for project viability: Case studies from Korean megaprojects,” *Int J Proj Manag*, vol. 35, no. 8, pp. 1683–1696, 2017, doi: 10.1016/j.ijproman.2017.07.011.
[3] K. A. Jehn, L. Greer, S. Levine, and G. Szulanski, “The Effects of Conflict Types, Dimensions, and Emergent States on Group Outcomes,” *Group Decis Negot*, vol. 17, no. 6, pp. 465–495, 2008, doi: 10.1007/s10726-008-9107-0.
[4] J. L. Brockman, “Interpersonal Conflict in Construction: Cost, Cause, and Consequence,” *J Constr Eng M*, vol. 140, no. 2, p. 04013050, 2014, doi: 10.1061/(asce)co.1943-7862.0000805.
[5] S. of E. and B. E. University Griffith, T. S. Nguyen, S. Mohamed, S. of E. and B. E. at G. University, K. Panuwatwanich, and S. of C. E. and T. (SIIT) Sirindhorn International Institute of Technology, “Stakeholder Management in Complex Project: Review of Contemporary Literature.,” *J Eng Proj Prod Management*, vol. 8, no. 2, pp. 75–89, 2018, doi: 10.32738/jeppm.201807.0003.
[6] T. H. Y. Li, S. T. Ng, and M. Skitmore, “Evaluating stakeholder satisfaction during public participation in major infrastructure and construction projects: A fuzzy approach,” *Automat Constr*, vol. 29, pp. 123–135, 2013, doi: 10.1016/j.autcon.2012.09.007.
[7] S. Olander, “Stakeholder impact analysis in construction project management,” *Constr Management Econ*, vol. 25, no. 3, pp. 277–287, 2007, doi: 10.1080/01446190600879125.
[8] S. Baek, W. Jung, and S. H. Han, “A critical review of text-based research in construction: Data source, analysis method, and implications,” *Automat Constr*, vol. 132, p. 103915, 2021, doi: 10.1016/j.autcon.2021.103915.
[9] L. Tang, L. Griffith, M. Stevens, and M. Hardie, “Social media analytics in the construction industry comparison study between China and the United States,” *Eng Constr Archit Management*, vol. 27, no. 8, pp. 1877–1889, 2020, doi: 10.1108/ecam-12-2019-0717.
[10] Z. Zhou, X. Zhou, and L. Qian, “Online Public Opinion Analysis on Infrastructure Megaprojects: Toward an Analytical Framework,” *J Manage Eng*, vol. 37, no. 1, 2021, doi: 10.1061/(asce)me.1943-5479.0000874.
[11] M. Wankhade, A. C. S. Rao, and C. Kulkarni, “A survey on sentiment analysis methods, applications, and challenges,” *Artif Intell Rev*, vol. 55, no. 7, pp. 5731–5780, 2022, doi: 10.1007/s10462-022-10144-1.
[12] J. Devlin, M.-W. Chang, K. Lee, and K. Toutanova, “BERT: Pre-training of Deep Bidirectional Transformers for Language Understanding,” *Arxiv*, 2018, doi: 10.48550/arxiv.1810.04805.
[13] P. Sharma and Y. Li, “Self-Supervised Contextual Keyword and Keyphrase Retrieval with Self-Labelling,” 2019, doi: 10.20944/preprints201908.0073.v1.

THE IMPORTANCE OF FEASIBILITY STUDY IN THE LAND SELECTION: EXAMPLE OF A RESIDENTIAL LAND

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Abstract

The construction industry requires large amounts of capital expenditure. There are many sub-units in the construction industry such as residential, commercial, road, bridge, etc. which is making the sector prone to many risks. One of the most important criteria at the beginning of the decision-making process in construction project is the selection of the right land. The cost analysis should be done correctly in the selection of the land and the benefit to be obtained from the project should be determined by considering all the details. Therefore, the feasibility study of the land can be compared with the investment cost and project benefit. In order to determine the suitability of the investment to be made, Net Present Value (NPV), Internal rate of return (IRR) and benefit/cost analysis criteria should be checked. This study covers a feasibility study for a project in Antalya. The study is aimed to calculate Net Present Value (NPV), Internal rate of return (IRR) and benefit/cost criteria. The purpose of this study is to emphasize the importance of feasibility study on land selection in projects. In the study, sample fields were selected for the purpose and feasibility studies were performed for these lands.

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Keywords: benefits of cost analysis, feasibility, housing project, IRR, NPV.

Introduction

Shelter has always been one of the most basic human necessities throughout history. Overcrowding of the population led to the creation of new development areas and the extension of construction outwards from the places designated as settlement centers as the historical process continued. As the population density rose as a result of this circumstance, new zoning areas were determined.

In a rapidly developing world, the basic need for housing and shelter is increasing day by day. This basic need is only for shelter for low-income groups. In addition to shelter, featured and certified dwelling structures are preferred for higher-income groups. The diversification of the housing sector for different income groups and the fact that this need has never diminished and even gradually increased in any period keep the interest of investors in this sector at a high level. Over time, the increase of investors in the housing sector, as well as the expansion of investment projects in each new project, has prompted other investors from other sectors to gravitate to this sector.

Decision-making process is one of the most critical factors in every sector. Making the appropriate decisions can have a positive or negative impact on every process from start to finish. To reduce uncertainties and ensure the successful completion of the project, it is necessary to think carefully and in detail about the decisions to be made on time, to consider all elements thoroughly, and to examine the options in detail. Every stage in the entire process, from the initial idea of the project to the completion of the project and bringing it to the sector, should be considered thoroughly, and all alternatives should be discussed in all detail in the decisions to be taken.

As in every sector, before investing in the housing sector, the investor considers his/her own capital and thinks thoroughly about which region and with which features he/she will invest in a housing project and decides accordingly. In the decisions taken, many factors such as the development of the district and neighborhood, especially the city where the project will be built, the income levels of the people who prefer the region, housing features such as the preferred indoor space, number of rooms, quality of materials used, etc. play an important role.

If the right decisions are not taken at the beginning or during the project, it is likely that the investor will not make the desired profit, incur losses, or even have undesirable consequences such as bankruptcy. All of the aforementioned negativities are not only project-based but may appear as failures in other investment processes of the investor, and gaining the trust of participants and customers in other projects may negatively affect the investor. The decision-making process should be carried out meticulously to avoid these negativities. Land selection is one of the most important stages of the decision-making process.

During land selection, the cost analysis should be done correctly, and the benefit to be obtained from the project should be determined by considering all the details. The feasibility study of the land enables a comparison of the cost required for the investment to be made and the benefits to be obtained from the project. Net Present Value (NPV), Internal rate of return (IRR), and cost/benefit analysis criteria should be checked to determine the suitability of the investment.

In this study, Net Present Value (NPV), Internal Rate of Return (IRR)i and cost/benefit criteria were calculated for residential lands in 4 different districts in Antalya province. The lands in question are located in the districts of Mollayusuf Mahallesi- Konyaaltı, Sütçüler Mahallesi- Kepez, Çağlayan Mahallesi- Muratpaşa and Altınkale Mahallesi- Döşemealtı.

Feasibility Study

Capital investment is required for the implementation of a construction project in any region. When the characteristics of the construction sector are analyzed, there is a high level of uncertainty. Therefore, a feasibility study is required before starting any project [10].

In the study prepared for the preparation and evaluation of investment projects, the issues related to investment and preparation of investment projects were examined in detail, and investment proposals based on the net present value and internal rate of return methods were discussed [6].

In the studies, Net present value (NPV), internal rate of return (IRR), and cost/benefit analysis were used as commonly used criteria to check the suitability of the project in the feasibility study of a housing project in the Pimpri Chinchwad area in India. The aim of this study was to determine whether the project is feasible or not [10].

In the study conducted in Malaysia, another country located in Asia, a feasibility study and economic evaluation research was conducted on Green Building projects to help the client decide whether the project is feasible and worth continuing [7]. In the study conducted in Hanoi, Vietnam, the potential for Construction and Demolition Waste (CDW) recycling facilities was evaluated by estimating the potential supply and demand and assessing the probable costs and benefits. NPV and IRR methods were also utilized in this evaluation [8].

In addition to housing projects, green building projects, and recycling facilities, feasibility studies were also carried out for investment projects such as irrigation canal construction projects and railway construction projects. In one of these studies, a feasibility study was carried out in the research to determine the suitability of the irrigation canal construction project in order to increase the yield in the fields in Indonesia [13]. Furthermore, in Tanjung Perak Port, Indonesia, a feasibility study was conducted as an intermediate model for the railway construction project, and the railway construction project was categorized as much as possible by determining the NPV, IRR, and benefit/cost ratio [1].

In order to emphasize the importance of feasibility study in the construction sector, due to the delay, cost, and other issues that directly and negatively affect the construction sector in Iraq, as well as other issues that affect the quality of construction projects, a study was conducted to assess the level of awareness of feasibility study in construction projects and to identify the effects of feasibility study in the construction sector, and to identify the causes of feasibility study violations in the construction sector [11].

If we examine the studies carried out in Turkey country, a thermal hotel project to be developed in Afyonkarahisar region was taken into consideration and SWOT analysis was used in the strategic evaluation of the project and, discounted cash flow method was used in the cost analysis. Net Present Value, Internal Rate of Return were calculated in the study [12]. The thesis study was carried out in different regions of the province of Istanbul, and the study was completed with a Financial Analysis study by making Residence, Home - Office, and Hotel Project Development in Kartal-Soğanlık Region and Residence, Office, Shopping Center, and Congress Hotel Project Development in Pendik Region [3].

Studies have been carried out in other sectors apart from the construction sector, and it aimed to produce kaolin from the Balıkesir - Sındırgı field to meet the needs of the ceramic enterprises in the region. It was recommended, that the selection between alternative investment projects should be made according to the NPV criterion [4].

Moreover, research conducted to provide information on economic internal profitability, which is a measure of how much the investment project will contribute to the national economy, was tested with methods using discounted cash flows, and calculations were made according to the internal profitability ratio, net present value, benefit/cost ratio and net benefit/cost ratio method [9].

In another study, revenue and expenditure forecasts in investment projects were mentioned. The study, by mentioning that the expenditures made in investment projects were often not completed within a year and that expenditures occur at different times during the project, and that the revenues to be obtained from the project cannot be collected at the same time; it was emphasized that revenues and expenditures were not at the same values. Noting that these value differences should be analyzed over similar time periods, it was explained that some of the valuation methods used in the calculations based on the estimates were Net Present Value (NPV), Internal Rate of Return (IRR), and Benefit/Cost Ratio [6]. In a different study, the methods of evaluating the economic efficiency of investment projects for the construction of industrial facilities of industrial organizations under uncertainty and risk were examined. In the study, NPV, and IRR examinations were studied for scenarios [5].

The purpose of feasibility study can be listed as follows.

1. Determine the benefit/cost ratio for the project
2. To determine the Net Present Value (NPV) and Internal Rate of Return (IRR) for the project.
3. Analyze the parameters to determine if the proposed project is appropriate.

Net Present Value (NPV)

The Net Present Value (NPV) method is a method of calculating the net value (net) at the present time. The present assumption is to explain that the initial time of the calculation coincides with the time the evaluation is carried out or in the 0 year period in the calculation of investment cash flow [13].

In order for a project to be accepted by this method, it must be equal to or greater than 1. Among alternative projects, the project, which has the largest ratio, is prioritized, with greater than 1. As with the NPV method, the selection and magnitude of the discount ratio to be used in this method affect the analysis results very much. The purpose of the method is to prioritize the project, which has the largest benefit/cost ratio in investments to be made, thus maximizing the investor's B/C ratio.
The formula used to calculate the NPV value is:

NPV=PWB – PWC

$$\mathrm{PWB} = \sum_{t-0}^{n} CBt(FEB)t \qquad (1)$$
$$\mathrm{PWC} = \sum_{t-0}^{n} CCt(FEB)t$$

PWB = Present Worth of Benefit;
PWC = Present Worth of Cost;
Cb = Cash flow benefit;

Cc = Cash flow cost;
FBP = Present Interest Factor;
n = Investment period;
t = Time period;

If the difference is positive, the project is accepted (NPV > 0). In the case of multiple projects, the project with the NPV high should be preferred. If NPV = 0, it is clear that annual acquisition flows barely cover operating costs and annual investment costs [6].

Internal Rate of Return (IRR)

Internal Rate of Return (IRR) is an interest rate (not bank interest) that describes the level of profit from a project or investment in percentage when the NPV value is equal to zero. IRR is the interest rate that illustrates that the benefits presented are equal to zero [13].

The formula used to calculate the IRR is;

$$\text{IRR} = iNPV0 + \frac{NPV0}{(NPV0 + NPV1)}\,(iNPV0 - iNPV1) \qquad (2)$$

iNPV0 = interest rate net present value at i0;
iNPV1 = interest rate net present value at I;
NPV0 = net present value at i0;
NPV = net present value at i.

In order for a project to be accepted, the calculated IRR investor must be greater than the minimum discount rate accepted. In a selection between alternative projects, the IRR largest project is prioritized. If the IRR has more than one option higher than the discount rate, the IRR higher investment project will take priority.

Benefit Cost Analysis

Benefit/Cost Ratio is calculated in two different ways. According to the first method, also called the most used profitability index, the Benefit/Cost Ratio is the ratio of the sum of the current values of the benefits (cash inflows) that a project will provide during its economic life, the sum of the costs (investment expenditures and other cash outputs) to the sum of the current values. The second method, called the benefit/cost ratio of investment, is calculated by dividing the total of net reduced cash flows into the reduced investment total.

$$BCR = \frac{PWB}{PWC} \qquad (3)$$

PWB = Present Worth of Benefit;
PWC = Present Worth of Cost.

In order for a project to be accepted by this method, it must be equal to or greater than 1. Among alternative projects, the project, which has the largest ratio, is prioritized, with greater than 1. As with the NPV method, the selection and magnitude of the discount ratio to be used in this method affect the analysis results very much. The purpose of the method is to prioritize the project, which has the largest benefit/cost ratio in investments to be made, thus maximizing the investor's B/C ratio [2].

Purpose of the Study

One of the most important stages at the beginning of all investment projects in the construction sector is the selection of the land. The benefit to be obtained from the project to be developed on the selected land is one of the most important items in terms of the evaluation of the project by the investor. Therefore, every detail, criterion, and all option must be evaluated in order to make the right decision in land selection. This is the same for housing projects as in other construction branches. In this study, the data required for the feasibility study were determined by literature research and expert opinions, NPV, IRR, and Benefit/Cost ratios were calculated, and the final ranking was made.

Within the scope of the study, 4 parcels where the housing project can be realized were selected. In the selection process, attention was paid to the fact that the lands were parcels designated as residential zoned and that they were located in areas with high housing density and preferred by buyers. For this study, surveys were conducted in the fields and regions, and expert opinions were obtained from previous articles, theses, and studies. With the identified data, NPV, IRR, and Benefit/Cost ratios were calculated on the lands, and the final ranking was aimed.

Location of the Case Study

According to TurkSTAT data published on February 6, 2023, Antalya province is the 5th largest city in Turkey with a population of 2,688,004 people and its surface area is approximately 20,177 km². According to TurkSTAT data published on February 6, 2023, there are 19 districts and districts including Akseki, Aksu, Alanya, Demre, Döşemealtı, Elmalı, Finike, Gazipaşa, Gündoğmuş, İbradı, Kaş, Kemer, Kepez, Konyaaltı, Korkuteli, Kumluca, Manavgat, Muratpaşa, Serik, and a total of 914 neighborhoods in these distributions.

As in Turkey in general, the demand for shelter is increasing day by day due to the growing population in Antalya. Due to important factors such as tourism, local and foreign settlers prefer Antalya province. An analysis of TurkSTAT data shows that the number of residential building permits issued by the issuance in 2022 in the districts where the study was carried out among 19 districts constitutes approximately 34% of the province in general and 45% of the occupancy permit.

Comparative Feasibility assessment of the predicted housing zones

NPV, IRR, and Benefit/Cost ratios were studied for the four parcels specified in the study area. The acceptances and assumptions made in the studies are as follows;

-In the determination of the Construction Area, the precedent rights determined for the lands and 30% of the area excluding the precedent were taken into consideration.
-For the Saleable Area, 20% of the construction area was deducted from the approximate construction area with the assumption that the common areas will be more because the immovables in Konyaaltı and Muratpaşa are qualified, 10% because the immovable in Döşemealtı is a villa, and 10% with the assumption that the common area of the immovable in Kepez district will be lower.
-Considering that the buildings to be built in Konyaaltı, Muratpaşa and Döşemealtı will be of higher quality, the cost item that constitutes the expense item has been taken higher than that of Kepez district.
-In the sales figures that make up the income, zero housing price averages were taken, taking into account the research made in the region. 3,100 USD/m2 for Muratpaşa, 1,150 USD/m2 for Kepez, 2.700 USD/m2 for Konyaalti, 2,300 USD/m2 for Döşemealtı were foreseen.
-The percentage of contractors in the regions is 40% for Muratpasa, 50% for Kepez, 44% for Konyaaltı, 45% for Dosemealti.
-The reduction rate for NPV is taken as 10%.

The results of the work carried out are as follows.

Table 1. Results Obtained

	Muratpaşa	*Kepez*	*Konyaaltı*	*Döşemealtı*
NPV (USD)	*1.832.292 USD*	*208.527 USD*	*1.635.589 USD*	*1.430.652 USD*
IRR	*31%*	*18%*	*25%*	*25%*
BenefitCost	*39%*	*19%*	*33%*	*31%*

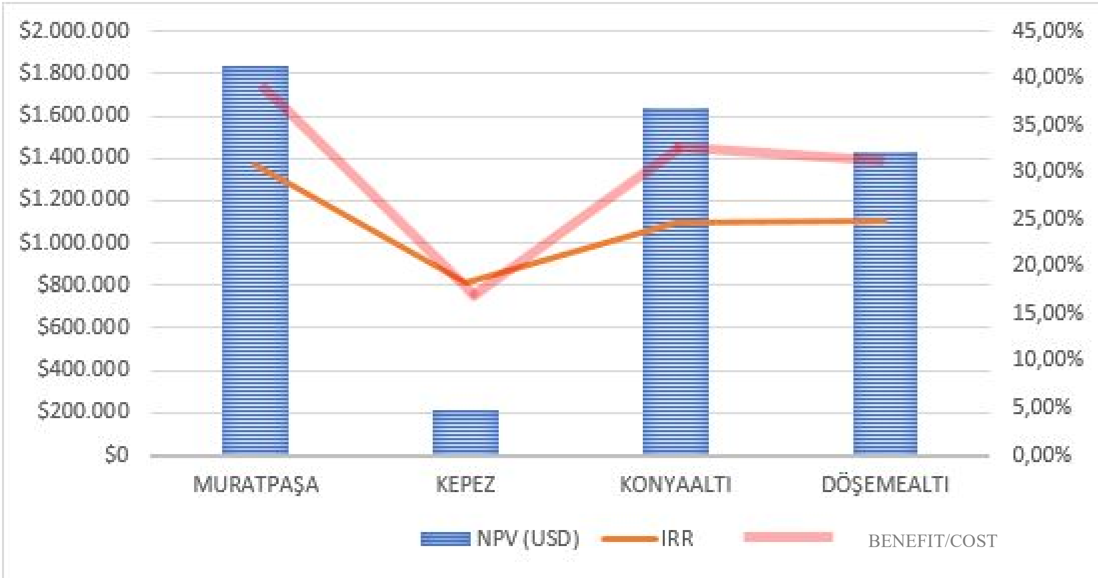

Figure 4. Graphical Display of Results

Table-1 shows the data obtained as a result of the study. Figure-4 is the graphical representation of the results obtained.

As can be seen from the results obtained, the district with the best Benefit/Cost ratio, NPV, and IRR results was calculated as Muratpaşa district.

Results

Within the scope of the research aiming at the selection of residential land, first of all, all the criteria that should be considered in the selection of an investment land were identified through other articles, research, theses, publications and interviews with experts.

Considering that housing projects were developed for all lands, NPV, IRR, and Benefit/Cost Ratios were determined by taking into account the income to be obtained from the lands in case of completion of the projects and the costs to be spent and ranking was made among the regions. As a result of the feasibility study, it was seen that the best alternative could be the land in Muratpaşa district.

Research and studies have shown that the proximity of the land to the center, the completion of the infrastructure and especially the high turnover to be obtained from the sale of housing, which constitutes the income item of the project, can be important items in the selection of the land.

When the NPV, IRR and Benefit/Cost Ratios are analyzed; it is contemplated that the investment can be considered for the land in Konyaaltı and Döşemealtı districts in addition to the land in Muratpaşa district. Due to the development of the Döşemealtı district, the increase in interest recently, and the expansion of detached housing throughout the country, it is thought that better results may be obtained in new studies to be conducted in the coming period.

In this study, the criteria are considered in terms of deciding on land selection at the beginning of a project have been shown with sample applications. The criteria, calculations, and acceptances in the study have been taken into account by considering the four selected lands, and do not cover the districts in general. All the details in the study are specific to the field and the process in which the research was conducted.

Finally, in all studies, including the decision-making to be carried out in these districts, land-specific criteria should be determined, research should be carried out, and a project-specific decision should be considered. In addition, the study was conducted on the data identified during the research process, and therefore, future research is recommended even for the same lands, during the investment decision-making process for the process outside the research.

References

[1] K. Arga, B. Susetyo, and S. Syafwandi, "FEASIBILITY STUDY OF A RAILWAY CONSTRUCTION PROJECT AS INTERMODAL TRANSPORTATION IN TANJUNG PERAK PORT," SINERGI, vol. 25, no. 1, p. 59, Nov. 2020, doi: 10.22441/sinergi.2021.1.008.

[2] Bostancı, B.. Taşınmaz Geliştirmede Değer Kestirim Analizleri ve İstanbul Konut Alanı Örneğinde Bir Uygulama. Ph.D. dissertation, Yıldız Technical Univ., İstanbul, Turkey,, 2008

[3] Çalışkan, G.. Gayrimenkul piyasalarinda proje geliştirme yöntemleri ve uygulamalar. Ph.D. dissertation, Halic Univ., İstanbul, Turkey,, 2011.

[4] Demirbugan, M. & . YATIRIM PROJELERİNİN DEĞERLENDİRİLMESİNDE NET BUGÜNKÜ DEĞER (NBD) VE İÇ KARLILIK ORANI (İKO) YÖNTEMLERİNİN KARŞILAŞTIRILMASI . Afyon Kocatepe Üniversitesi İktisadi ve İdari Bilimler Fakültesi Dergisi , 10 (2) , 1-15 ,Dec. 2008. Retrieved from https://dergipark.org.tr/en/pub/akuiibfd/issue/1628/20397

[5] M. M. Gayfullina, G. Z. Nizamova, D. R. Musina, Z. A. Gareeva, and A. Yu Tumanova, "An integrated approach to assessing the effectiveness of investment projects for the construction of industrial facilities under uncertainty," IOP Conference Series: Earth and Environmental Science, vol. 751, no. 1, p. 012074, Apr. 2021, doi: 10.1088/1755-1315/751/1/012074.

[6] Gedik, T. , Akyüz, K. C. & Akyüz, İ. YATIRIM PROJELERİNİN HAZIRLANMASI VE DEĞERLENDİRİLMESİ (İç Karlılık Oranı ve Net Bugünkü Değer Yöntemlerinin İncelenmesi) . Bartın Orman Fakültesi Dergisi , 7 (7) , 51-61 ,Mar. 2005. Retrieved from https://dergipark.org.tr/en/pub/barofd/issue/3407/46885

[7] F. M. Halil, N. M. Nasir, A. A. Hassan, and A. S. Shukur, "Feasibility Study and Economic Assessment in Green Building Projects," Procedia - Social and Behavioral Sciences, vol. 222, pp. 56–64, Jun. 2016, doi: 10.1016/j.sbspro.2016.05.176.

[8] N. H. Hoang et al., "Financial and economic evaluation of construction and demolition waste recycling in Hanoi, Vietnam," Waste Management, vol. 131, pp. 294–304, Jul. 2021, doi: 10.1016/j.wasman.2021.06.014.

[9] Mandacı, İ. Yatirim projelerinin ulusal ekonomi açisindan degerlendirîlmesînde gôlge fîyatlar, ekonomîk îç kârlilik analîzlerî ve bîr sinai yatirim projesîne uygulanmasi. Ph.D. dissertation, Marmara Univ., İstanbul, Turkey,, 1992

[10] Maske, P. B., & Gaikwad, A. K.. Feasibility study for a residential construction project: a case study. International Research Journal of Engineering and Technology, (05), 3984, May. 2021.

[11] S. R. Mohammed, H. I. Naji, and R. H. Ali, "Impact of the Feasibility Study on the Construction Projects," IOP Conference Series: Materials Science and Engineering, vol. 518, no. 2, p. 022074, May 2019, doi: 10.1088/1757-899x/518/2/022074.

[12] F. Taktak and H. Demir , "Termal Otel Geliştirme: Afyonkarahisar Örneği", Harita Teknolojileri Elektronik Dergisi, vol. 2, no. 1, pp. 20-35, Mar. 2010.

[13] Z. Zakia, M. Safriani, N. Radianica, and M. F. Ikhwali, "Economic Feasibility Study on The Development of Irrigation Channels," International Journal of Engineering, Science and Information Technology, vol. 2, no. 1, pp. 131–138, Dec. 2021, doi: 10.52088/ijesty.v2i1.217.

Theory of Information in Construction – Implementation in Critical Infrastructures exposed to Extreme events

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Abstract

The Theory of Information in Construction based on the hypothesis that failures in critical infrastructures (C.I.) are the result of loss of control in the information system of the CI as a result of information overflow of the system. The theory is established on four phases: (I) Statistical analyses: Probability Density Function of incoming events (PDF), Cumulative Distribution Function (CDF), Power function expressing the magnitude of events, and Scatter analysis; (II) Information Constraint (IC) expressing the capacity if the system, (III) Control circuits (feed-back loops), and (IV) Artificial Intelligence, Machine learning, Artificial Neural Network. The hypothesis of the theory is that failures, deficiencies, accidents and cascading failures are the result of an overflow of information in the system beyond the system's Information Constraint (IC). A similar hypothesis also refers to the performance of critical infrastructures, exposed to extreme abnormal events, caused by extreme events such as climate change, terrorism and seismic events. The events put the critical infrastructures in an extreme situation causing high risk to the continuity of performance of the CI, affecting vital services to civil society. This paper proposes a novel method for multi-hazard risk assessment of overhead transmission lines (OTL) grid. The main objective is to estimate the annual risk using failure rates estimated from historical failure data and modify them by reanalysis data and a dynamic Bayesian scheme. For this purpose, a comprehensive database of power grid supply failures is gathered. ANN is implemented to predict the incoming events, assess the risk and propose preventive activities.

Keywords: Construction Defects, Critical Infrastructures, Quality Control, Resilience, Risk Management and Assessment, Artificial Intelligence, Machine learning.

1. Introduction

Energy supply continuity management is vital to support, prevent, respond to, manage and recover from fallouts of an incidents or a disruptive undesired event. It assists in maintaining uninterrupted availability of all resources required for the continuous provision of essential services.

Extreme events such as climatic hazards, geo-hazards, potential terrorist attacks, rocket impact, explosion, and other man-made threats may lead to loss of Power Transmission Grid functionality and consequentially, interruption or operational disruption of vital services, and cause severe loss to critical facilities operations. Such events may develop cascading and rippling effects in other critical facilities, and consequentially might cause environmental contamination, injuries, fatalities, and systemic failure at the state level. Therefore, it is critical to understand, assess and manage risks associated with power disruptions to enhance its reliability and ensure uninterrupted power supply and the continuous performance of critical operational services.

The complexity of electricity networks makes it vulnerable to extreme events consequences. As compared to random failures in another infrastructures, extreme events or terrorist attacks specifically targeting Power Transmission Grid can result in high impact failure and be followed by serious consequences.

Energy continuity planning is that part of operational risk management that establishes which are the correct reactions and the cost-effective measures to be taken when a disruptive event occurs, to avoid energy supply interruptions and which strategies take place for proactive avoidance of such events and to maintain the performance of critical Infrastructures robust and operational during emergency times.

The present research focuses on the development of AI based analytical tools for the assessment and mitigation of the vulnerability of Overhead Power Transmission Grids under extreme events.

2. **Literature review**

The hypothesis of the theory is that failures, deficiencies, accidents and progressive failures are the result of the flow of information in the system beyond the possible capacity (its Information Constraint). A similar hypothesis also applies for the continuous perfoamce of Critical Infrastructures that are exposed to unusual events, according to (N. Yonat, S. Isaak and I. M. Shohet , 2022)[7] additionally, Global climate change the cause of extreme variation in phenomena such as extreme temperature regime, extreme precipitation patterns, and storms all of which cause critical infrastructures face extreme service conditions and in high risk of the continuous performance of the infrastructures and civil society in general and the citizens in particular.

Climate change creates unusual events, manifested in extreme winds, heat and cold waves.

Fractals were found in all research subjects. Fractals in PDF that is, the same curves repeat at every scale and in every part of the sample. Fractals Fourier Transform of the sample show the same frequency occurrences in each segment on the frequency axis, the failure curves also show a repeat occurrence, and in the spatio-temporal curve in each axis.

According to the research of Yonat Niv and Shohet Igal M." Complex Infrastructure Systems Analysis and Management, a Case-Study" (2023)[8], The behavior of the number of faults, on the grid axis, it behaves in the form of a fractal, So the main function consists of a series of functions distributed in the same way and vice versa.

According to the research of (Heron and Reason 1997)[1] for knowledge sharing we see a direction of developing integrated systems engineering experience and machine learning.

Failure rates in assessing the risks of the transmission lines - In the literature there are two main approaches to reliability depending on the weather**.**

1. Using a **Markov chain** model with two or more states (Billinton et al. 2002)[5]. However, this method is not suitable for large real-time systems (Panteli and Mancarella, 2015)[3].
2. Simulations using **Monte Carlo** is another relevant approach (Panteli and Mancarella, 2017)[2].

failure rate, the most basic parameter in reliability assessment, calculated primarily by calculating the **mean value** based on several years of statistics similar to the first article published on reliability assessment Billinton and Bollinger (1968)[6].Since then, several researchers have noted that extreme weather events are the main cause of transmission line failures. This article (Solheim and Kjolle, 2016)[4] presents a method for calculating the risk assessment in overhead transmission lines based on past failure rates annual failure rates, and updated using Bayesian update. Finally, a sample scenario based on Monte Carlo simulation for the transmission lines was carried out to simulate the occurrence of failure events, and then, the annual exceedance probabilities of the loss.

2.1. Summary review main failure factors:

The major root causses of failures in overhaed power grids are:

- Extreme weather such as wind, snow and cold loads
- Oil pipelines
- Emergency shutdown of a hazardous liquid pipeline
- Man-made damages

2.2. Summary of literature review by topics:

Figure 1 delineates the topics classification of the literature on failures in Overhead Power Supply lines.

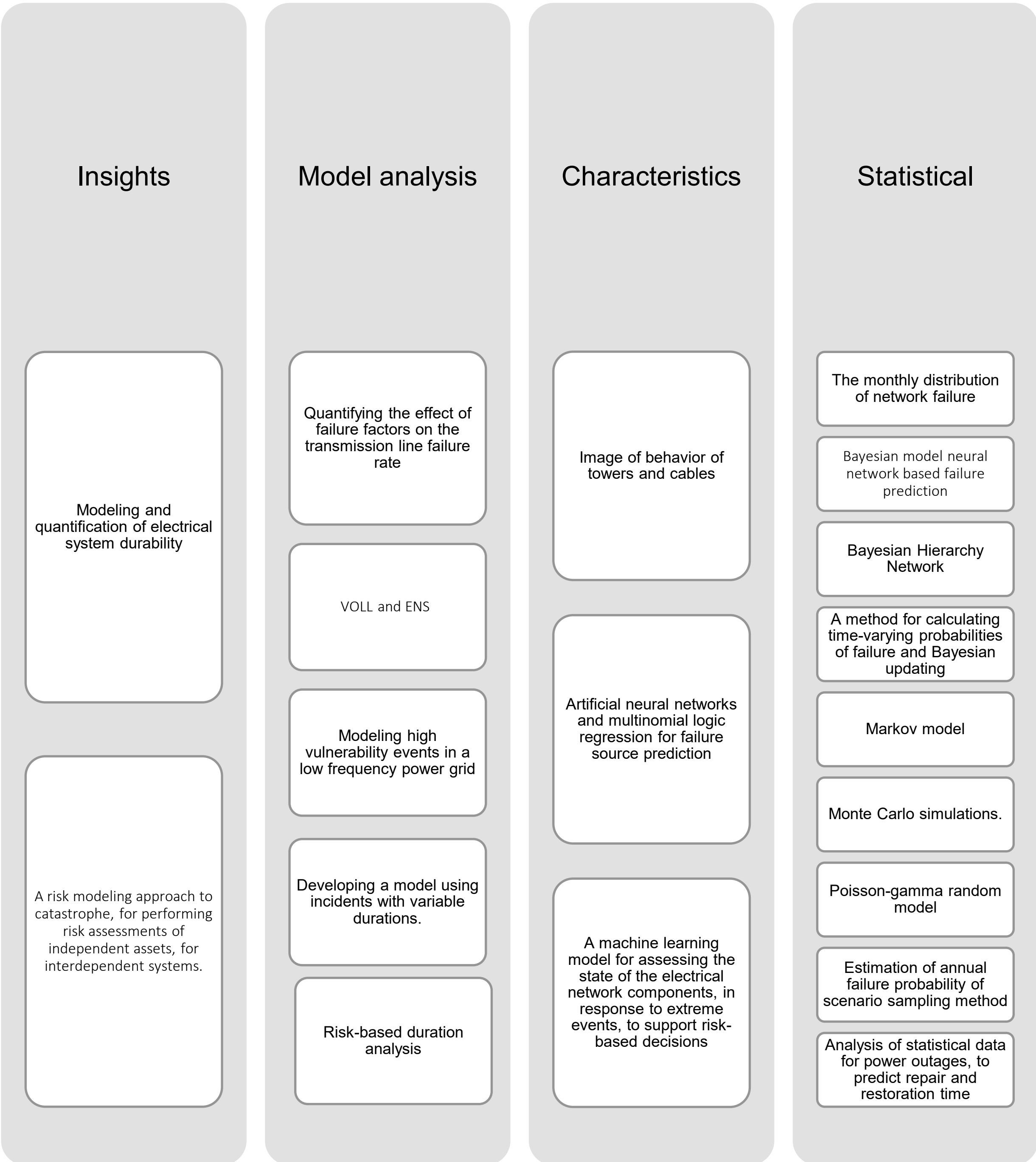

Figure 1 - Topics classification of the literature review

3. Methodology

3.1. The research framework

The research method steams from the Theory of Information and combines statistical features of the failure events with learning tools: AI, ML.

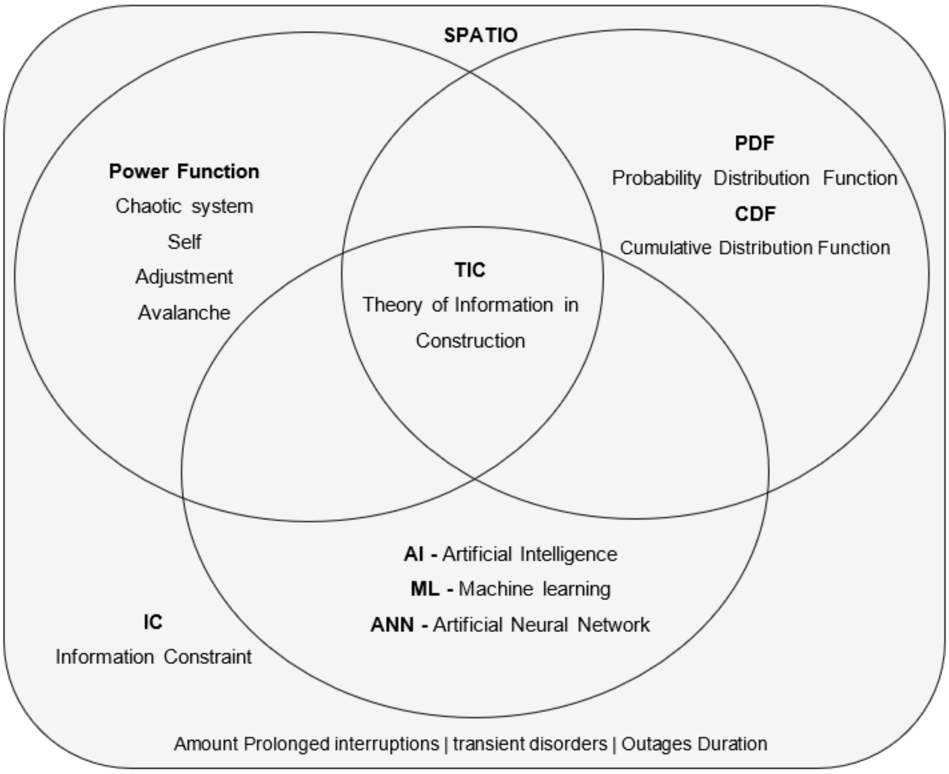

Figure 2 - research framework

3.2. The research method

The research followed five phases:

Phase I - Locating data base for research on non-delivery minute data on the website of the Israel Electricity Company [9].

Phase II - Data cleansing and establishment of a database encompassing about 69.3 thousand faults in the electricity network over a period of the years 2017-2022.

Phase III - Statistical analyses of the data, including: adjustment Probability Distribution Function (PDF), adjustment Cumulative Distribution Function (CDF), Power Function (PF), Scatter Analysis, Correlation and Regression analyses.

Phase IV - Data network construction in the method Artificial Neural Network (ANN): district (4) → sub stat (192) → line (3,648) → Prolonged interruptions (40,653) & transient disorders (28,672).

Phase V - Adjusting and building the predictive Machine Learning model employing Artificial Intelligence tools.

Using methods of: Linear regression, supervised learning, support vector machine, logistic regression, ensemble methods, reinforcement learning, naïve bayes etc. When the final run of the method will be done according to the statistical analyses of the data.

4. Findings

The model is developed as a network receiving incoming given events, the events are learned and characterized by Probability Distribution Functions (PDF) as a means for precise prediction of the **magnitude** and **location** of future events. The frequency of events that will take place in the coming year (planning horizon) and their **effect** on the power grid (and finding the high impact lines), If no preventive actions will be taken is derived from the PDF and Power Function. The model investigates the **relationship** between transient faults and prolonged outages in order to find the root-causes of the prolonged power supply interruption.

4.1. Phase II – statistics

4.1.1. Probability Distribution Function:

Histogram Mean outages duration (minutes) for the years 2017-2021

Distribution: Exponential
Expression: EXPO (48.5)
Square Error: 0.002572
Chi Square Test: Corresponding p-value < 0.005

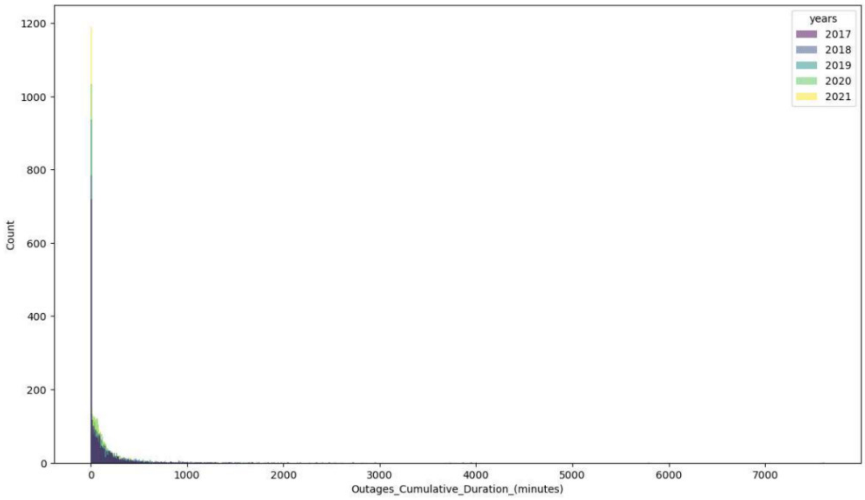

Figure 3 – Histogram of Mean outages duration in minutes

Histogram Amount Prolonged interruptions for the years 2017-2021.

Distribution: Exponential
Expression: 0.999 + EXPO (3.13)
Square Error: 0.000400
Chi Square Test: Corresponding p-value < 0.005
Kolmogorov-Smirnov Test: Corresponding p-value < 0.01

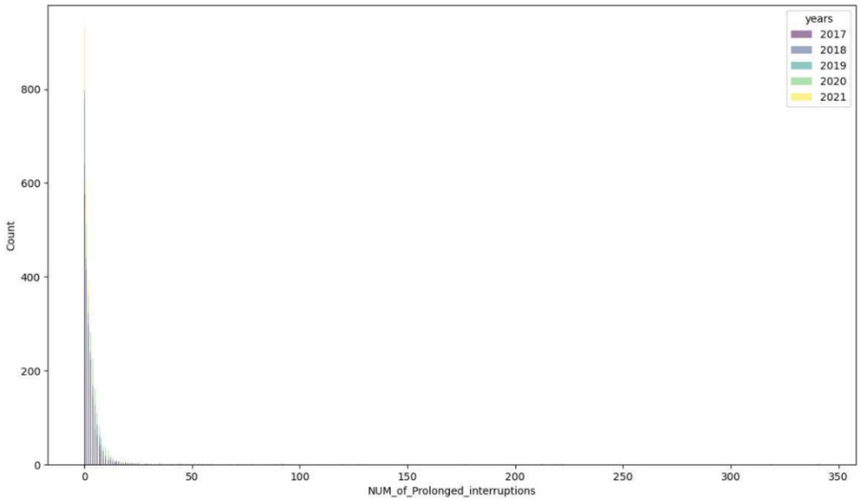

Figure 4 - Histogram of Amount Prolonged interruptions

Histogram Energy not supplied (ENS*)* for the years 2017-2021.

Distribution: Exponential
Expression: -0.001 + EXPO (7.08)
Square Error: 0.000516
Chi Square Test: Corresponding p-value < 0.005

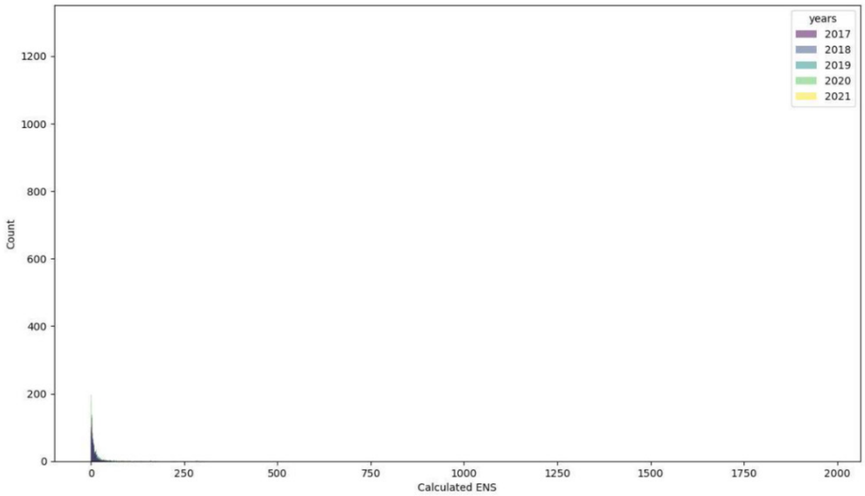

Figure 5 - Histogram of Energy not supplied

Conclusions from the statistical analyses:

- Histograms and fitting an exponential distribution, in confidence tests with α <0.05
- Proof that the data behaves according to the "fractal" theory.
- Proof of the "Pareto" principle when about 10% of faults have the highest impact.

4.1.2. Correlation

The heat map and Correlation matrix shows the significance and correlation of dependence between the variables relativel, the darker the color, the higher the dependence between the variables. And represents the correlation number when the value is 1 the relationship is the strongest between the variables. A high dependency can be seen between NUM_of_Prolonged_interruptions and Calculated_ENS with a value of 0.75. and a high dependency between NUM_of_Prolonged_interruptions and Outages_Cumulative_Duration_(minutes) with a value of 0.65

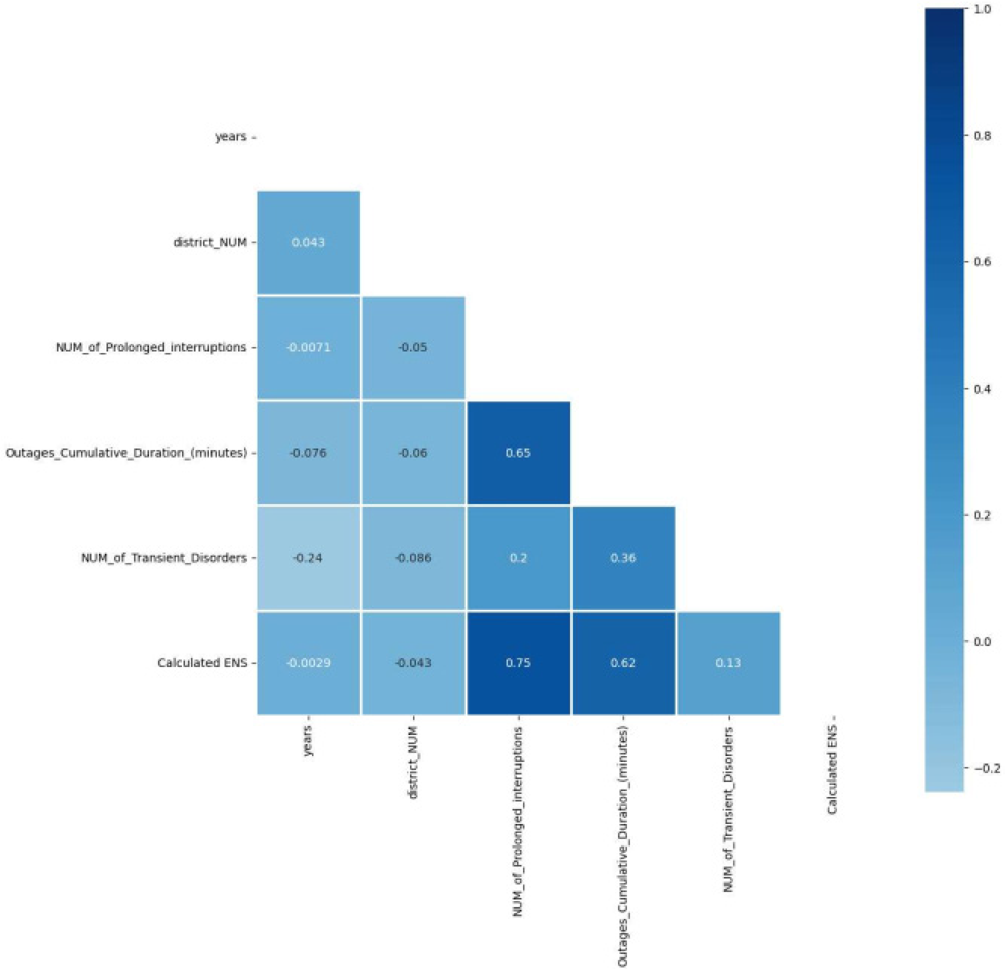

Figure 7 - Heat Map of Correlation

	year	district_NUM	NUM_of_Prolonged_Interruptions	Outages_Cumulative_Duration_(minutes)	NUM_of_Transient_Disorders	Calculated_ENS
year	1.000000	0.042923	-0.007104	-0.076369	-0.238758	-0.001162
district_NUM	0.042923	1.000000	-0.049564	-0.060488	-0.086402	-0.056679
NUM_of_Prolonged_interruptions	-0.007104	-0.049564	1.000000	0.653726	0.201077	0.746802
Outages_Cumulative_Duration_(minutes)	-0.076369	-0.060488	0.653726	1.000000	0.364463	0.636800
NUM_of_Transient_Disorders	-0.238758	-0.086402	0.201077	0.364463	1.000000	0.155384
Calculated_ENS	-0.001162	-0.056679	0.746802	0.636800	0.155384	1.000000

Figure 6 - Correlation matrix

4.1.3. Regression

A regression analysis on the timeline for the fault data shows a direct relationship, because over the years the unreliability of the network has started to decrease.

Graphs of NUM_of_Prolonged_interruptions and Calculated ENS are the same, which proves a direct relationship between them.

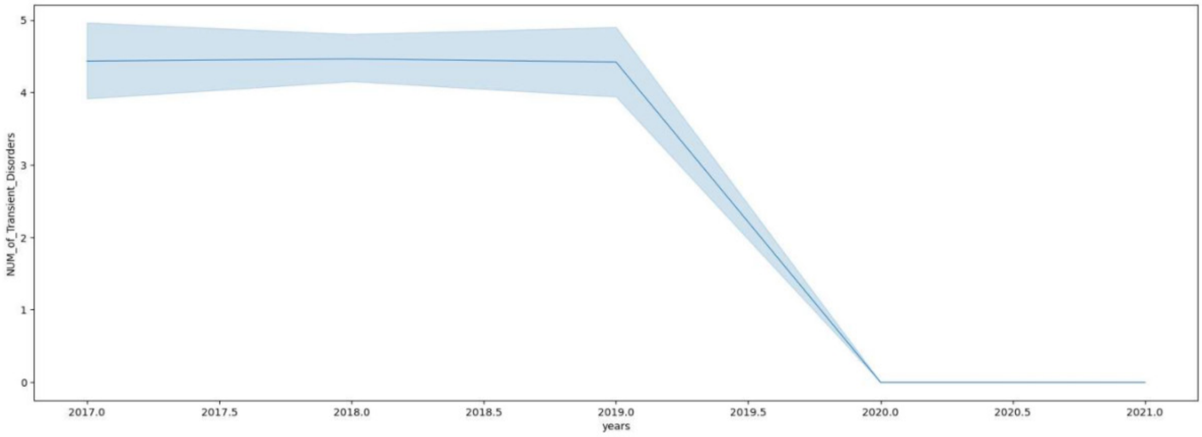

Figure 10 - Regression between NUM of Transient Disorders to Time

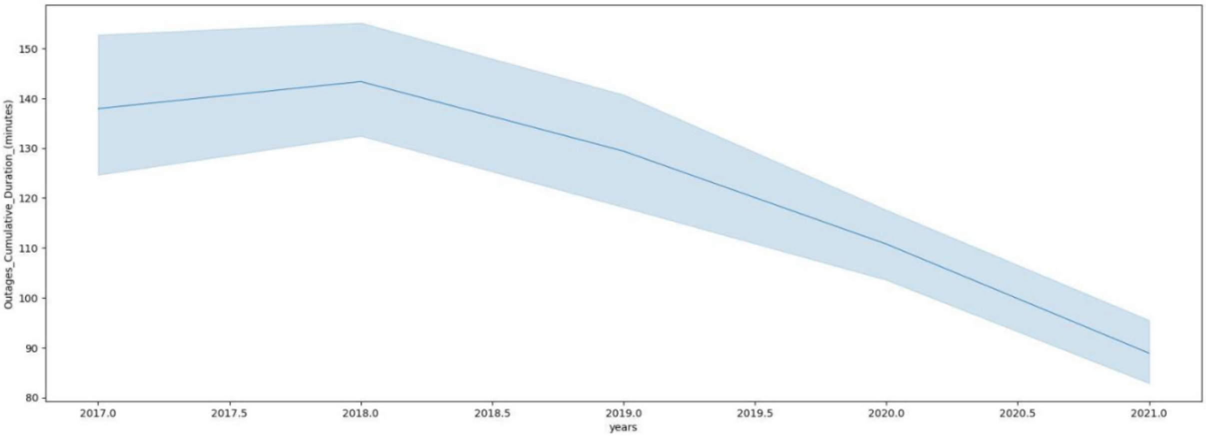

Figure 9 - Regression between Outages Cumulative Duration in minutes to Time

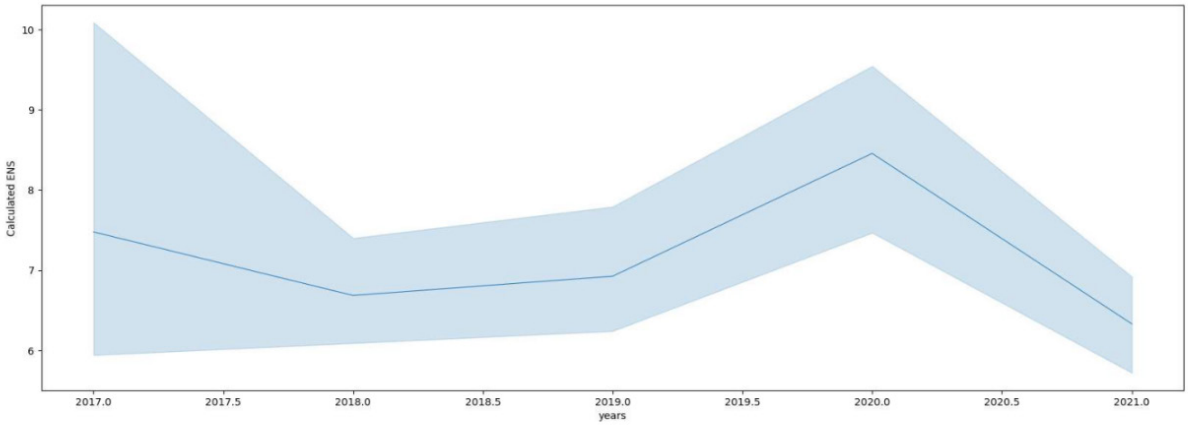

Figure 8 - Regression between ENS to Time

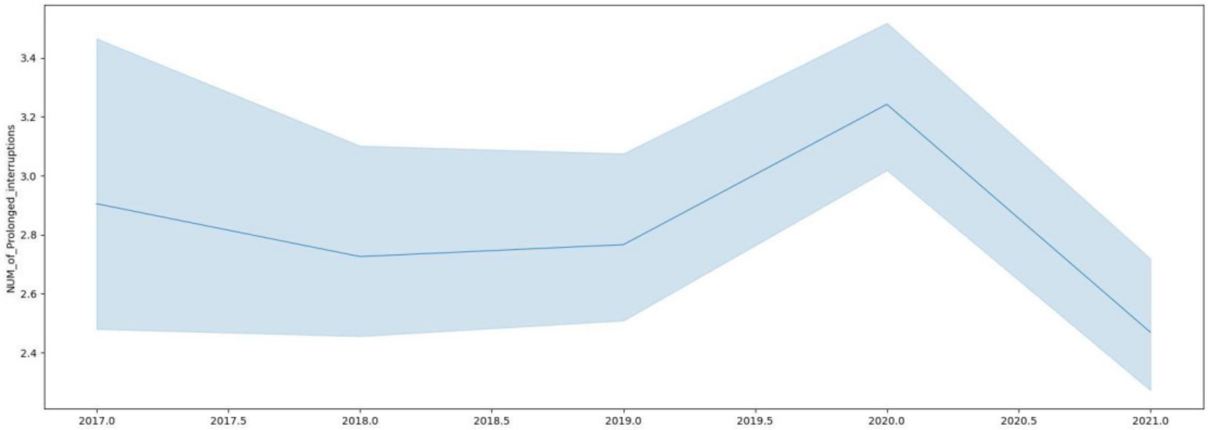

Figure 11 - Regression between NUM of Prolonged interruptions to Time

4.2. ***Phase IV - Artificial Neural Network (ANN)***

Artificial Neural Networks are biologically inspired systems which convert a set of inputs into a set of outputs by a network of neurons, where each neuron produces one output as a function of inputs.

Artificial Neural Networks may be used to identify and classify outstanding failures from recorded data base that caused severe outages at power transmission lines.

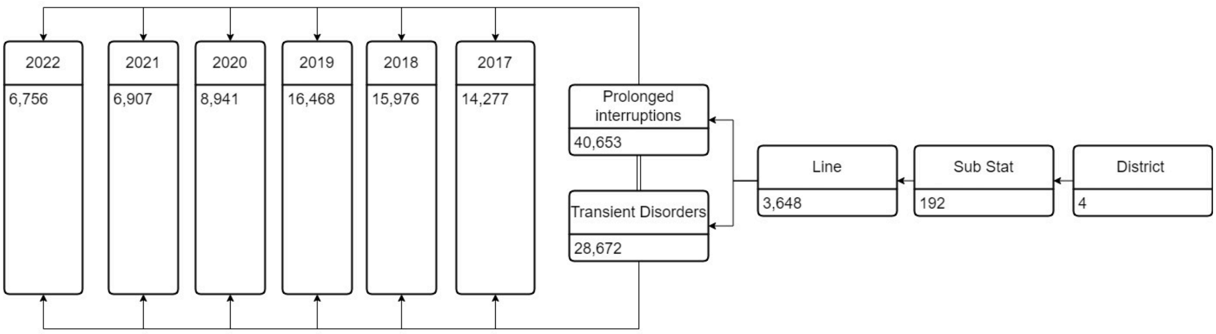

Figure 12 - diagram of model Artificial Neural Network

4.3. ***Phase V – Artificial Intelligence (AI) by Machine Learning (ML)***

The model is based on machine learning and receives input of its faults and characteristics, the model learns from the data and its behavioral patterns, adjusting the model accordingly.
The purpose of the model, is the identification of failure factors prior to a state of collapse in the power grid, analysis of the vulnerability of the electricity network and establishment of risk management tools for proactive prevention of prolonged power supply interruptions events.
The model is based on the “Forecast” technique - A forecast model is a mathematical or statistical representation of a system or process used to predict future outcomes or events. It utilizes historical data and various variables to generate forecasts or predictions about future conditions or trends. These models help in decision-making, resource allocation, risk assessment, and strategic planning.

5. Conclusions

The paper introduces the implementation of Statistical Inference tools based on TIC for prediction prevention of failure events in Overhead Power Grid. The research includes five phases as follows:

- **Phase I -** Locating data base.
- **Phase II** - Data cleansing
- **Phase III** - Statistical analyses.
- **Phase IV -** Artificial Neural Network (ANN)
- **Phase V** - Building the predictive Machine Learning model employing Artificial Intelligence tools.

The statistical tests stood with p-value < 0.01.

The research is innovative and creative due to the use of (ANN) Artificial Neural Networks may be used Prediction and prevention of failures in electricity transmission systems.

The model built as a network receiving incoming given events, the events are learned and characterized as a means for precise prediction of the **magnitude** - **location** - **effect** of future events.

So, in the prediction platforms preventive activity can be performed that saves millions of dollars to maintain the reliability of the electricity grid.

References

[1] J. Heron and P. Reason, "A Participatory Inquiry Paradigm," Qualitative Inquiry, vol. 3, (3), pp. 274, 1997. https://journals.sagepub.com/doi/abs/10.1177/107780049700300302?journalCode=qixa. DOI: 10.1177/107780049700300302.

[2] M. Panteli, C. Pickering, S. Wilkinson, R. Dawson and P. Mancarella, "Power System Resilience to Extreme Weather: Fragility Modeling, Probabilistic Impact Assessment, and Adaptation Measures," *Tpwrs,* vol. 32, *(5),* pp. 3747-3757, Sep 01, 2017. Available: https://ieeexplore.ieee.org/document/7801854. DOI: 10.1109/TPWRS.2016.2641463.

[3] Panteli, Mathaios & Mancarella, Pierluigi. (2015). Influence of extreme weather and climate change on the resilience of power systems: Impacts and possible mitigation strategies. Electric Power Systems Research. 127. 10.1016/j.epsr.2015.06.012.

[4] O. R. Solheim, T. Trotscher and G. Kjolle, "Wind dependent failure rates for overhead transmission lines using reanalysis data and a bayesian updating scheme," in Oct 2016, pp. 1-7Available: https://ieeexplore.ieee.org/document/7764104. DOI: 10.1109/PMAPS.2016.7764104.

[5] Peng Wang and R. Billinton, "Reliability cost/worth assessment of distribution systems incorporating time-varying weather conditions and restoration resources," Tpwrd, vol. 17, (1), pp. 260-265, Jan 2002. Available: https://ieeexplore.ieee.org/document/974216. DOI: 10.1109/61.974216

[6] Roy Billinton, Kenneth E. Bollinger 1968 “Transmission System Reliability Evaluation Using Markov Processes”, DOI: 10.1109/TPAS.1968.292051

[7] Yonat, N., Isaak, S., & Shohet, I. M. (2022). Complex Infrastructure Systems Analysis and Management, a Case-Study. Open Engineering Inc. 10.31224/2624

[8] Yonat, N., & Shohet, I. M. (2023). Theory of Faults (ToF). Open Engineering Inc. 10.31224/2389

[9] https://www.iec.co.il/content/info/filespages/dataaminut

[10] Yonat, N., & Shohet, I. M. (2022). “Theory of Information in Construction- TIC”

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WORKFORCE CHALLENGES AND STRATEGIES OF TOP CONTRACTORS IN THE UNITED STATES

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Abstract

The construction industry is plagued with numerous workforce challenges. The skilled craft labor shortage has been a consistent and unfortunate recurring struggle for the past three decades. Moreover, recent trends show that the construction workforce has been aging rapidly, aggravating the labor shortage challenge and negatively impacting project performance in terms of cost, schedule, and safety. Studies in the existing literature have highlighted the different workforce challenges and strategies to address them and mitigate their impact, mostly from a research perspective. However, no research has yet studied how top contractors in the United States are dealing with these workforce issues. The purpose of this study is to analyze the challenges the top contractors in America face and synthesize the strategies they employ to address these challenges and increase workforce performance. To achieve the research objective, the authors analyzed recent annual reports of top contractors and summarized the challenges they face and the policies and strategies they have institutionalized to respond to current challenges.

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Keywords: construction, challenges, contractors, strategies, labor shortage

1. Introduction and Background

The US construction industry stands at a crossroads. The United States infrastructure us deteriorating and is in dire need of replacement as we continue to face a major shortage in the labor force [1]. The construction industry struggles with plenty of workforce challenges. The skilled craft labor shortage has been an unfortunately recurring challenge for the past few decades [2]. Moreover, trend data shows that the construction workforce has been rapidly aging, exasperating the labor shortage challenge and negatively impacting project performance in terms of safety, schedule, and cost [3]. To add, the construction industry suffers from a lack of workforce diversity, especially gender diversity, where women make up less than 4% of the construction craft workforce in the United States [4]. Despite this small female participation percentage, the construction industry faces major struggles relating to the treatment of women in the construction industry. One recent study concluded that women in construction are more likely, on average to feel disrespected at work, be subjected to derogatory remarks, and be treated unprofessionally [5]. Moreover, the construction industry has failed to consistently attract and retain skilled workers due to the negative industry image problems, an aging workforce, and insufficient training [6]. Furthermore, the industry continues to suffer from inadequate frontline supervision and failure of frontline supervisors to provide the necessary information, planning, support, and motivation [7], especially as frontline supervisors have the essential responsibility of ensuring safe and healthy work practices, and they create the missing communication link between the craft workforce and management [8], [9]. Several research efforts have extensively highlighted the importance and major influence frontline supervisors have on construction productivity [10]–[12].

There is an apparent consensus by industry leaders and experts that the construction industry will look radically different over the next 20 years [13]. With the increasing level of sophistication in the construction industry, construction companies are turning to unique and innovative approaches to gain a competitive advantage [14], from increasingly adopting construction technologies [15], to increasingly using as-built models to meet the maintenance needs of the future [16], and to highlighting the need for workforce training [17].

Construction workers are the cornerstone of the construction industry, especially as they constitute a sizable segment of overall production costs. Consequently, their performance and productivity are essential to the successful completion of construction projects [18]. One major problem facing the construction industry is the drop in the rate of worker productivity and performance [19]. Because construction workers play an outsized role in overall construction productivity, it is important to understand the factors of what impacts their productivity and performance. Factors involving tools and construction equipment, materials, and technologies were found to have a major impact on worker performance [20]. For instance, a study that examined the impact of 13 types of technologies on construction workforce performance and information access found that the use of several information, material, and equipment technologies offers a statistically significant improvement of average workforce performance in the construction industry [21]. One study that analyzed the impact of administrative and computer skills of construction workers showed that such skills increase performance and information access [22]. Another study found that ethnic and gender crew diversity improves worker performance and information access in the construction industry [23]. Other determinants of workforce productivity and performance include: an increased level of supervision [24], effective communication and information flow [25], sufficient financial compensation [24], adequate work planning of construction tasks, methods, and materials [26], continuous work training and education, [24], and the effective implementation safety measures [27].

While workforce challenges in the construction industry and strategies to mitigate their impact have been thoroughly studied in existing literature, no research has yet studied the challenges the leading contractors in the United States face or the strategies they employ to address them and increase workforce performance. This study aims to analyze the challenges the top contractors in the US face and synthesize the strategies they employ to address those challenges and increase workforce performance.

2. Methodology

This study aims to analyze the challenges the top contractors in the US face and synthesize the strategies they employ to address those challenges or increase workforce performance. To achieve the research objective, the authors analyzed recent annual reports and websites of the top 10 contractors in the United States and summarized the challenges they face and the policies and strategies they have institutionalized to respond to current challenges and increase workforce performance and productivity. The authors analyzed the contents of annual reports and other available resources on their websites and highlighted those major challenges they face and policies they institute. In this study. Project-specific challenges or strategies are beyond the scope of this analysis.

The results of the analysis are represented in word clouds in Figures 1 & 2. A word cloud is a visual portrayal of word/phrase frequency in the composed text. The more often a word/phrase appears in composed text, the larger it appears in the developed image [28]. A larger font size in the graphic indicates a higher frequency of occurrence in the text or the narrative. This visualization is a helpful tool to assist investigators in evaluating textual data and highlighting words/phrases with high frequency [29].

The list of top 10 contractors used for this analysis was selected based on the list of top contractors from Engineering News-Record (ENR). ENR provides the engineering and construction news, analysis, commentary, and data that construction industry professionals need to do their jobs more effectively. Additionally, ENR reports on the top design firms, both architects and engineers, and the top construction companies and contractors as well as projects in the United States and around the world [30].

Table 1 shows the list of the top 10 ENR contractors that were analyzed [31], their year of founding, annual revenue, and references/sources used in the analysis.

Table 1: List of ENR top 10 contractors used for analysis [31]

2022 Rank	Contractor	Year Founded	Revenue	References/Sources Used
1	The Turner Corp.	1902	$14.4B	Website [32], Annual Report [33]
2	Bechtel	1898	$17.6B	Website [34], Annual Report [35]
3	Kiewit Corp.	1884	$13.7B	Website [36]
4	STO Building Group	1971	$8.1B	Website [37], Annual Report [38]
5	Flour	1912	$15.6B	Website [39], Annual Report [40]
6	The Whiting-Turner Contracting Company	1909	$9.2B	Website [41], Annual Report [42]
7	DPR Construction	1990	$6.8B	Website [43]
8	Skanska USA	1887	$17.2B	Website [44], Annual Report [45]
9	Clark Construction Group	1906	$5.0B	Website [46]
10	AECOM	1990	$13.3B	Website [47], Annual Report [48]

3. Results and Analysis

The results of the analysis in this study are portrayed in Figures 1 & 2. Figure 1 shows a word cloud of the major challenges top contractors face, while Figure 2 shows a word cloud of the strategies they employ to address them or increase workforce performance.

Figure 1: Word cloud of major challenges that top contractors mentioned

In Figure 1, we can observe a word cloud representation of the of the major challenges that top contractors face that they have mentioned throughout their reports and websites. As can be seen, labor shortage was the primary challenge contractors face. All of the 10 top contractors discussed labor shortage as a problem they struggle with. This is consistent with what we see across the literature in construction research as this is a problem the industry has been struggling with for decades [2]. The second biggest challenge contractors faced was having to deal with COVID-19 and its impacts. Such a challenge, which was mentioned by nine of the 10 companies, strained the workforce in addition to the skyrocketing material cost, supply-chain bottlenecks and overall industry-wide disruptions. COVID-19 presents as a major challenge as this analysis refers to reports developed for periods during the pandemic. However, it is unclear whether this will only be temporary problem, or if COVID-19 will have other long-term impacts on the industry. Due to the labor shortage and COVID-19, companies are facing rising labor costs and are forced to employ workers without the sufficient amount of necessary skills to perform their jobs. All of these factors lead to a decrease in productivity and construction output. Another challenge companies mentioned was the aging workforce of the United States. Research suggests that the median age of the construction workforce is projected to rise to from 42.9 in 2020 to over 46 by 2030 [1]. Moreover, two of the contractors had struggles with discrimination and harassment, and one of them was sued for racial discrimination and was forced to settle the lawsuit. This is not surprising given the nature of the workforce culture of the construction industry, especially as one study found that construction workers are more likely to be treated unprofessionally and subjected to derogatory remarks at work compared to the national workforce [5]. Furthermore, contractors are struggling to recruit and retain workers, especially in light of competition from other industries and workers deciding to retire early. Finally, immigration restrictions has been limiting the contractors' ability to hire foreign workers as a backstop to fill the gap in the skilled labor shortage in the construction industry in the US.

Figure 2: Word cloud of strategies top contractors indicated they use to address challenges or increase performance

In Figure 2, we can observe a word cloud representation of the of the major strategies that top contractors employ to address the challenges they face or improve productivity that they have mentioned throughout their reports and websites. As can be seen, increasing diversity and inclusion is one of the main policies contractors use to address their challenges, as it was mentioned by all 10 contractors. Women make up less than 4% of the construction labor force and other minority groups are underrepresented in the industry [4]. Contractors realize that women and minority groups form a well of untapped labor potential that can fill the labor shortage gap, and diversifying the workforce can help attract more women and minorities into the labor force. Additionally, contractors are hyper-focused on workforce training and development to give their workers the necessary skills to do the job, and also offering them the needed mentorship and sponsorship to guide them in their career. Moreover, contractors continue improve their safety procedures and strive for a zero-incident goal in an effort to protect their employees and create a safe working environment. Several Companies are offering their workforce leadership training to build up future leaders in their companies. Furthermore, contractors are attempting to recruit students directly out of high schools and colleges, and are directly engaging with employees to listen to their needs. Still, in an effort to retain their workforce, contractors are starting to offer better compensation and benefits, focusing on health and wellness of their workforce, streamlining the promotion process, and one is even offering stock options for workers. In order to improve productivity, one company is increasing the level of frontline supervision. Finally, because of the limited available on-site labor, two contractors are increasingly using offsite fabrication to decrease the amount of on-site construction working hours.

4. Conclusion, Limitations, and Future Work

The construction industry continues to struggle with numerous workforce challenges. There has been a consistent skilled craft labor shortage that has been unfortunate recurring problem for the past three decades. This study aims to analyze the challenges the top 10 ENR contractors in America face and synthesize the list of strategies they employ to address those challenges or increase workforce performance. The results of the analysis show that major challenges contractors face include labor shortage, COVID-19, labor cost, unskilled labor, decreased productivity, an aging workforce, discrimination and harassment, industry competition, workforce recruitment and retainment challenges, early retirement, and immigration restrictions. In an effort to address such challenges and increase workforce performance, contractors have employed several policies and strategies. Those include: increasing diversity and inclusion in the workforce, workforce training and development, improving safety procedures, offering mentorship and sponsorship, recruiting students out college and high school, offering leadership training, offering better compensation and benefits, focusing on health and wellness of the workforce, engaging with employees, improving frontline supervision practices, streamlining the promotion process, offering employees stock options, and moving to offsite fabrication.

While this study presents a content analysis of the annual reports and websites of the top 10 ENR contractors to identify the major challenges they struggle with and the strategies they use to limit the impact of those challenges and increase performance, we are limited to what the contractors write down in their reports and websites. Therefore, this analysis may not have the full scope of the issues they face, as some companies may be reticent about sharing and detailing all the problems they have. Future research can build on this study and attempt to analyze the challenges and policies of a significantly larger set of top contractors to get a better picture of the status of challenges in the construction industry, including small and medium sized contractors.

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References

[1] Construction Industry Institute, “Workforce 2030: What You Need to Know Now About Your Future Workforce,” Construction Industry Institute, Austin, TX, US, Final Report FR-370, 2021.
[2] Construction Industry Institute, “Is There a Demographic Labor Cliff that Will Affect Project Performance,” Construction Industry Institute, Austin, TX, RT-318-11, 2016.
[3] T. Taylor, H. Karimi, P. Goodrum, and M. Albattah, “Is There a Demographic Labor Cliff that Will Affect Project Performance,” Construction Industry Institute, Austin, TX, RT-318-1, 2016.
[4] US Bureau of Labor Statistics, “Employed Persons by Detailed Occupation, Sex, Race, and Hispanic or Latino Ethnicity,” 2021. https://www.bls.gov/cps/cpsaat11.htm
[5] B. A. Ramadan, T. R. B. Taylor, K. J. Real, and P. Goodrum, “The Construction Industry from the Perspective of the Worker’s Social Experience,” in *Construction Research Congress 2022*, Arlington, Virginia: American Society of Civil Engineers, Mar. 2022, pp. 611–621. doi: 10.1061/9780784483985.062.
[6] R. L. Tucker *et al.*, “Key Workforce Challenges Facing the American Construction Industry An Interim Assessment,” Center for Construction Industry Studies, Report No. 3, 1999.
[7] G. A. Howell, “What is Lean Construction? IGLC7,” *University of California, Berkeley, CA, USA*, 1999.
[8] B. Ramadan, H. Nassereddine, T. R. B. Taylor, K. Real, and P. Goodrum, “Impact of Skill Proficiencies on Frontline Supervision Practices in the Construction Industry,” in *Proceedings of the Creative Construction e-Conference (2022)*, 2022. doi: https://doi.org/10.3311/CCC2022-024.
[9] B. O. Uwakweh, “Effect of Foremen on Construction Apprentice,” *J. Constr. Eng. Manage.*, vol. 131, no. 12, pp. 1320–1327, Dec. 2005, doi: 10.1061/(ASCE)0733-9364(2005)131:12(1320).
[10] N. Gerami Seresht and A. R. Fayek, “Factors influencing multifactor productivity of equipment-intensive activities,” *IJPPM*, vol. 69, no. 9, pp. 2021–2045, Jul. 2019, doi: 10.1108/IJPPM-07-2018-0250.
[11] K. N. Hewage, A. Gannoruwa, and J. Y. Ruwanpura, “Current status of factors leading to team performance of on-site construction professionals in Alberta building construction projects,” *Can. J. Civ. Eng.*, vol. 38, no. 6, pp. 679–689, Jun. 2011, doi: 10.1139/l11-038.

[12] M. Liberda, J. Ruwanpura, and G. Jergeas, “Construction Productivity Improvement: A Study of Human, Management and External Issues,” in *Construction Research Congress*, Honolulu, Hawaii, United States: American Society of Civil Engineers, Mar. 2003, pp. 1–8. doi: 10.1061/40671(2003)5.
[13] M. J. Ribeirinho *et al.*, “The Next Normal in Construction: How disruption is reshaping the world’s largest ecosystem,” McKinsey & Company, 2020.
[14] A. Renz, M. Z. Solas, M. Buhler, P. Gerbert, S. Castagnino, and C. Rothballer, “Shaping the Future of Construction. A Breakthrough in Mindset and Technology,” World Economic Forum, Cologny, Switzerland, 2016.
[15] G. B. Dadi, H. Nassereddine, T. R. Taylor, R. Griffith, and B. Ramadan, “Technological Capabilities of Departments of Transportation for Digital Project Management and Delivery,” No. NCHRP Project 20-05, Topic 52-19, 2022.
[16] H. Nassereddine, B. Ramadan, Y. Li, R. Sturgill, and P. Patel, *Practices for the Collection, Use, and Management of Utility As-Built Information*. Washington, D.C.: Transportation Research Board, 2023, p. 27034. doi: 10.17226/27034.
[17] R. H. Assaad, I. H. El-adaway, M. Hastak, and K. LaScola Needy, “The Impact of Offsite Construction on the Workforce: Required Skillset and Prioritization of Training Needs,” *J. Constr. Eng. Manage.*, vol. 148, no. 7, p. 04022056, Jul. 2022, doi: 10.1061/(ASCE)CO.1943-7862.0002314.
[18] C. S. Okoro, I. Musonda, and J. Agumba, “Identifying Determinants of Construction Worker Performance on Construction Sites: A Literature Review,” *IJIMT*, pp. 60–63, 2017, doi: 10.18178/ijimt.2017.8.1.703.
[19] M. E. Shehata and K. M. El-Gohary, “Towards improving construction labor productivity and projects’ performance,” *Alexandria Engineering Journal*, vol. 50, no. 4, pp. 321–330, Dec. 2011, doi: 10.1016/j.aej.2012.02.001.
[20] J. Dai, P. M. Goodrum, and W. F. Maloney, “Construction Craft Workers’ Perceptions of the Factors Affecting Their Productivity,” *J. Constr. Eng. Manage.*, vol. 135, no. 3, pp. 217–226, Mar. 2009, doi: 10.1061/(ASCE)0733-9364(2009)135:3(217).
[21] B. Ramadan, H. Nassereddine, T. R. B. Taylor, and P. Goodrum, “Impact of Technology Use on Workforce Performance and Information Access in the Construction Industry,” *Frontiers in built environment*, 2023, doi: 10.3389/fbuil.2023.1079203.
[22] B. Ramadan, H. Nassereddine, T. R. B. Taylor, and P. Goodrum, “Impact of Administrative and Computer Skill Proficiency on Workforce Performance and Information Access in the Construction Industry,” in *2023 Canadian Society of Civil Engineers Annual Conference*, 2023.
[23] B. Ramadan, H. Nassereddine, T. Taylor, and P. Goodrum, “Impact of Crew Diversity on Worker Information Access and Performance,” in *ISARC. Proceedings of the International Symposium on Automation and Robotics in Construction*, IAARC Publications, 2023.
[24] J. K. Yates, *Global engineering and construction*. John Wiley & Sons, 2006.
[25] H. Lingard, K. Brown, L. Bradley, C. Bailey, and K. Townsend, “Improving Employees’ Work-Life Balance in the Construction Industry: Project Alliance Case Study,” *J. Constr. Eng. Manage.*, vol. 133, no. 10, pp. 807–815, Oct. 2007, doi: 10.1061/(ASCE)0733-9364(2007)133:10(807).
[26] U. C. Gatti and G. C. Migliaccio, “A study on the influence of construction workers’ physiological status and jobsite environment on behaviour and performance,” in *49th ASC Annual International Conference Proceedings*, Citeseer, 2013, pp. 10–13.
[27] A. Enshassi, S. Mohamed, and S. Abushaban, “Factors Affecting The Performance of Construction Projects in the Gaza Strip,” *JOURNAL OF CIVIL ENGINEERING AND MANAGEMENT*, vol. 15, no. 3, pp. 269–280, Jun. 2009, doi: 10.3846/1392-3730.2009.15.269-280.
[28] R. Atenstaedt, “Word cloud analysis of the BJGP,” *British Journal of General Practice*, vol. 62, no. 596, pp. 148–148, 2012.
[29] A. A. Karakhan, J. Gambatese, D. R. Simmons, and C. Nnaji, “How to Improve Workforce Development and Sustainability in Construction,” in *Construction Research Congress 2020*, Tempe, Arizona: American Society of Civil Engineers, Nov. 2020, pp. 21–30. doi: 10.1061/9780784482872.003.
[30] Engineering News-Record, “ENR About US,” 2023. https://www.enr.com/aboutus
[31] Engineering News-Record, “ENR 2022 Top 400 Contractors,” 2023. https://www.enr.com/toplists/2022-Top-400-Contractors-1-preview
[32] Turner Construction Corp., 2023. https://www.turnerconstruction.com/
[33] Turner Construction Corp., “Diversity, Equity & Inclusion 2021 Equity Audit Report,” Turner Construction Corporation, New York, NY, 2022. [Online]. Available: http://report.tcco.site/books/jyfz/?utm_source=tcco+website&utm_medium=internet&utm_campaign=equity+report#p=1
[34] Bechtel, 2023. https://www.bechtel.com/
[35] Bechtel, “Bechtel Report 2021, Partners in Progress,” Bechtel, 2022. [Online]. Available: https://www.bechtel.com/Bechtel/media/html/Bechtel-Report-2021/index.html
[36] Kiewit, 2023. https://www.kiewit.com/
[37] STO Building Group, 2023. https://stobuildinggroup.com/
[38] STO Building Group, “Environmental Social & Governance Report 2023,” STO Building Group, 2023. [Online]. Available: https://stobuildinggroup.com/social-responsibility-report/
[39] Flour, 2023. https://www.fluor.com/
[40] Flour, “Future-Fit, 2022 Integrated Report,” Flour Construction, 2022. [Online]. Available: https://s201.q4cdn.com/930516572/files/doc_financials/2022/ar/2022-Fluor-Integrated-Report.pdf
[41] The Whiting-Turner Contracting Company, 2023. https://www.whiting-turner.com/construction/
[42] The Whiting-Turner Contracting Company, “Supply Chain Challenges & Current Market Conditions,” 2022. [Online]. Available: https://static1.squarespace.com/static/5f310d7ab4e00e41d4834c60/t/628275ecc506571a1028f97f/1652717044238/B3_Supply+Chain+Challenges+and+Current+Market+Conditions_Quirk-Cheff.pdf
[43] DPR Construction, 2023. https://www.dpr.com/
[44] Skanska, 2023. https://group.skanska.com/
[45] Skanska, “Annual and Sustainability Report 2022,” Skanska, 2022. [Online]. Available: https://group.skanska.com/493785/siteassets/investors/reports-publications/annual-reports/2022/annual-and-sustainability-report-2022.pdf
[46] Clark Construction Group, 2023. https://www.clarkconstruction.com/
[47] AECOM, 2023. https://aecom.com/
[48] AECOM, “Delivering Today and More Tomorrow, 2022 Annual Report,” AECOM, 2022. [Online]. Available: https://aecom.com/wp-content/uploads/documents/reports/aecom-annual-report.pdf

A MACHINE LEARNING FRAMEWORK FOR CONSTRUCTION PLANNING AND SCHEDULING

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Abstract

In building and infrastructure projects, construction planning and scheduling refer to a process of defining project policies and procedures and breaking them down into specific construction activities, which significantly affect various aspects including cost, time, safety, and quality. Construction planning and scheduling have been shifting from manual to automatic with the adoption of information and communication technologies, and numerous methods, such as optimization algorithms, have also been used in construction planning and scheduling. However, due to the multiplex, evolving, and unstructured nature of sites and tasks, construction planning and scheduling with previous technologies and methods do not work well for practical applications, especially during the execution phase of building and infrastructure projects. With the development of artificial intelligence in recent years, machine learning that is able to deal with complex, dynamic, and uncertain things shows the potential to assist with that problem. To structure and standardize construction planning and scheduling with the application of machine learning, this study proposes a framework with reinforcement learning, imitation learning, and transfer learning, and discusses their respective benefits and limitations. With the proposed framework, application effectiveness and efficiency could be enhanced and application clarity and repeatability cloud be promoted.

Keywords: artificial intelligence, deep learning, imitation learning, reinforcement learning, transfer learning.

1. Introduction

In building and infrastructure projects, construction planning and scheduling refer to a process of defining project policies and procedures and breaking them down into specific construction activities [1]. During this process, a detailed construction plan associated with a schedule is developed for executing a project under various constraints (e.g., sequence, resource) to minimize budget overruns, the risk of delays, as well as safety and quality issues [1]. Construction planning and scheduling typically involve the following steps: first, the scope of a project is defined; next, specific activities to be completed are identified; then, dependencies between activities (e.g., finish to start, start to start, finish to finish) are identified; after, resources needed to complete each activity (e.g., labor, material, equipment) are determined; and finally, a plan associated with a schedule that estimates duration and assigns start and end times to each activity is developed [2].

Before the advent of modern technologies, including computers, software and networks, construction planning and scheduling were conducted primarily by hand with simple tools such as pencils and paper, which can be time-consuming and error-prone [3]. To identify potential delays and bottlenecks, coordinate activities and allocate resources in a simple and visual format, graphical and network representations have been developed for construction planning and scheduling [4]. For example, the Gantt chart is a type of bar chart that illustrates the start and end times of activities [5]; the activity-on-arrow (AOA) is a type of network diagram where arrows and nodes represent activities and events, respectively [6]; and the activity-on-node (AON) is a type of network diagram where nodes and arrows represent activities and dependencies between them, respectively [7]. Over the past several decades, construction planning and scheduling have been shifting from manual to automatic with the adoption of information and communication technologies [8]. One class of traditional tools used to promote the automation of construction planning and scheduling is project management software. Project management software, such as Microsoft Project and Oracle Primavera, is a type of computer application, which can effectively facilitate construction planning and scheduling [9]. Another relatively new class is based on building information modeling (BIM). BIM is a digital representation of projects that supports different aspects of construction management. BIM-based construction planning and scheduling, such as Autodesk Navisworks and Bentley Synchro, can leverage information stored, simulate and optimize strategies and solutions, and visualize potential conflicts and problems [10][11].

With the development of mathematics and engineering knowledge, numerous methods have been used in construction planning and scheduling. Once the duration of different activities has been determined, the overall duration of a project can be estimated applying the critical path method (CPM) to identify the longest stretch of dependent activities from a deterministic perspective [12], while the program evaluation and review technique (PERT) can be utilized to calculate the expected overall duration of a project with optimistic, pessimistic and most likely estimates from a stochastic perspective [13]. To coordinate activities considering the allocation of resources, resource leveling is applied to adjust the start and end times of activities with resource constraints while balancing the supply and demand of resources [14], and resource smoothing is utilized to adjust the start and end times of activities while reducing the fluctuations in resource demand [15]. To select strategies and solutions for construction planning and scheduling, multiple categories of optimization algorithms, including heuristics, mathematical programming, and metaheuristics, are widely used. Heuristics, such as greedy algorithm, are a category of optimization algorithms that applies experience-based strategies and is easier to understand and implement in contrast to more rigorous optimization algorithms [16]. Mathematical programming, such as linear programming, integer programming, and dynamic programming, is a category of optimization algorithms that formulates problems and tasks with mathematical models and provides strategies and solutions with more quality assurance [17]. Metaheuristics, such as genetic algorithm, simulated annealing, and tabu search, are a category of optimization algorithms that combines random and local search mechanisms, handles a wider range of problems and tasks, and solves large-scale problems and tasks in a faster way [18].

Nowadays, artificial intelligence has been sweeping the world. As a subset of artificial intelligence, machine learning is being extensively used in various industries, including the construction industry. Machine learning enables machines, such as computers and robots, to learn from data and make predictions and decisions without being explicitly programmed [19]. Therefore, compared to other algorithms and models, machine learning is smarter when dealing with complex, dynamic, and uncertain things. In building and infrastructure projects, due to the multiplex, evolving, and unstructured nature of sites and tasks, construction planning and scheduling with previous methods do not work well for practical applications, especially during the execution phase. In this context, machine learning provides a chance for a new round of transformation and upgrading of construction planning and scheduling. In recent years, machine learning has been applied to the field of construction planning and scheduling, such as the development of a construction activity schedule and a tower crane lifting plan [20][21]. However, construction planning and scheduling with the application of machine learning are currently at an early stage, and machine learning still has great application potential to explore. To enhance effectiveness and efficiency and promote clarity and repeatability, it is useful to establish a framework to structure and standardize construction planning and scheduling with machine learning. Considering the sequential characteristics of construction planning and scheduling, three machine learning methods, namely reinforcement learning, imitation learning, and transfer learning, can be suitable and play a significant role in this process [22][28][33].

With the above background, this study aims to propose a framework with reinforcement learning, imitation learning, and transfer learning for construction planning and scheduling. The rest of this paper is organized as follows. In Section 2, the concept and classification of three machine learning methods are introduced. Section 3 details the proposed framework and discusses the benefits and limitations of three machine learning methods. Conclusions and outlook are provided in Section 4.

2. Machine learning methods

In this section, the concept and classification of three machine learning methods, namely reinforcement learning, imitation learning, and transfer learning, are introduced.

2.1. Reinforcement learning

Reinforcement learning is a type of machine learning method where the agent interacts with the environment and receives rewards by taking actions to learn a policy that maximizes accumulated rewards over time [22]. Reinforcement learning can be classified into different categories based on the corresponding criteria, and there are five main criteria listed as follows: (1) The first criterion is whether to build a model of the environment involving transition probabilities between states, actions, and rewards. Model-based learning uses the built model to predict the outcomes of state-action pairs and update the policy, while model-free learning directly updates the policy through trial and error without the built model [23]. (2) The second criterion is how the agent updates the policy. On-policy learning updates the policy according to the experience generated from the policy that is currently being used, whereas off-policy learning updates the policy according to the experience generated from a different policy than the current one [24]. (3) The third criterion is how the agent selects actions. Value-based learning selects actions that maximize the value function of state-action pairs, while policy-based learning selects actions based on the probability distribution of state-action pairs [25]. (4) The fourth criterion is whether the agent adapts and reacts to changes in the environment in real time. On-line learning constantly interacts with the environment and updates the policy according to the rewards received, whereas off-line learning updates the policy according to a dataset of experience that was collected from the environment beforehand [26]. (5) The fifth criterion is the number of agents interacting with the environment. Single-agent and multi-agent learning interact with the environment using a single agent and multiple agents, respectively [27].

2.2. Imitation learning

Imitation learning is a type of machine learning method where the agent is trained to perform a task by imitating the behavior of human experts and then learns to perform the task relying on its own [28]. Imitation learning can be implemented using different approaches, and there are four main approaches listed as follows: (1) The first approach is behavioral cloning which learns a policy by directly mapping states to actions observed from human expert demonstrations [29]. (2) The second approach is dataset aggregation which learns a policy by iteratively aggregating self-generated data in addition to human expert demonstrations [30]. (3) The third approach is inverse reinforcement learning which infers underlying rewards from observed human expert demonstrations [31]. (4) The fourth approach is generative adversarial imitation learning which uses a generative adversarial network to learn a policy that is indistinguishable from human expert demonstrations by the discriminator [32].

2.3. Transfer learning

Transfer learning is a type of machine learning method where the knowledge learned from a source task is transferred to a different but related target task, namely a trained model from the source task is fine-tuned in the target task [33]. Transfer learning can be implemented using different approaches, and there are four main approaches listed as follows: (1) The first approach is domain adaptation which adapts a model trained on the source task to the target task with a different data distribution [34]. (2) The second approach is multi-task learning which trains a model on multiple related tasks simultaneously [35]. (3) The third approach is one-shot learning which adapts a model trained on the source task to the target task with limited labeled data [36]. (4) The fourth approach is zero-shot learning which adapts a model trained on the source task to the target task without any labeled data [37].

3. Machine learning framework for construction planning and scheduling

In this section, the framework with reinforcement learning, imitation learning, and transfer learning is detailed, and their respective benefits and limitations are discussed.

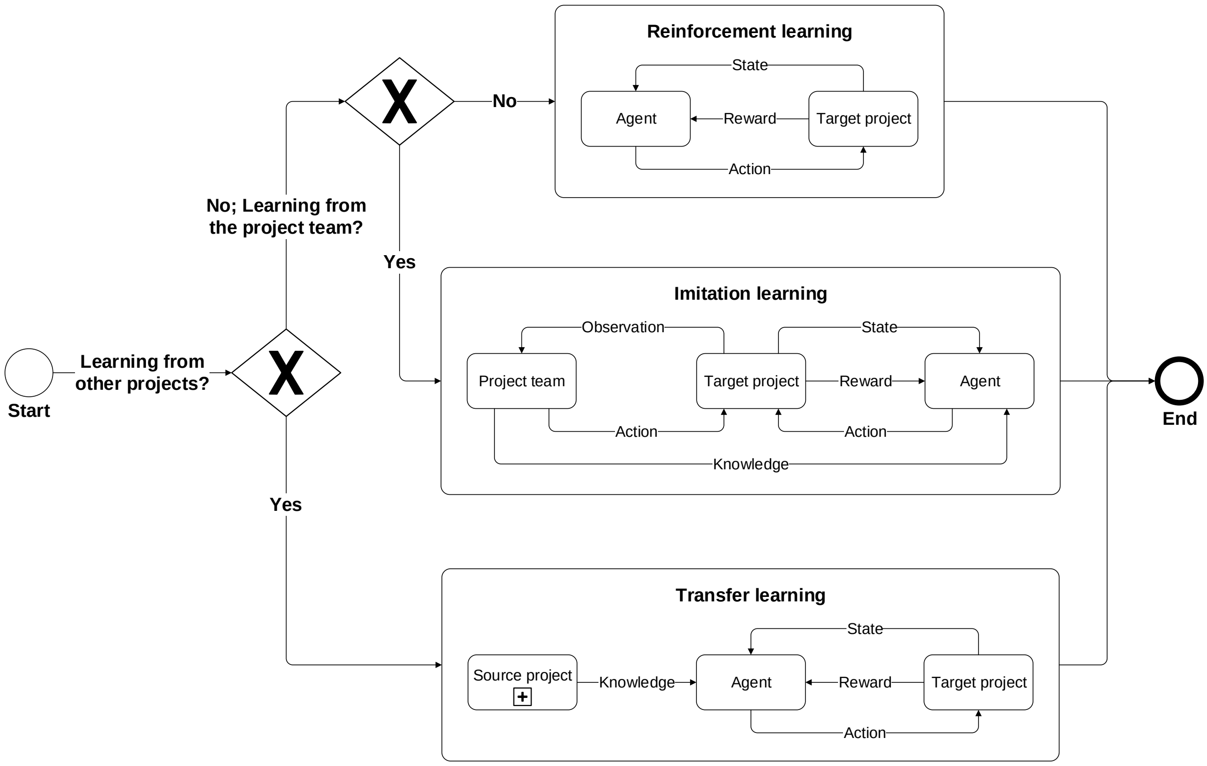

Fig. 1. Machine learning framework for construction planning and scheduling.

The proposed framework consists of three situations, as shown in Fig. 1. If the agent learns neither from other projects nor from the project team, then reinforcement learning will be used, which is Situation 1. If the agent learns not from other projects but from the project team, then imitation learning will be used, which is Situation 2. If the agent learns from other projects but not from the project team, then transfer learning will be used, which is Situation 3. For construction planning and scheduling, specific problems and corresponding tasks that determine how these three machine learning methods model should be clearly defined, and the development of a detailed construction plan associated with a schedule needs to explicitly identify project objectives, specifications, and constraints for formulating problems and tasks. Next, the three situations with different machine learning methods are elaborated on in the following subsections, respectively.

3.1. Situation 1 with reinforcement learning

In Situation 1 with reinforcement learning, there are five components, namely target project, agent, state, action, and reward. The target project is seen as an environment in reinforcement learning, and it refers to the system where the agent interacts. The scope of the target project has a great impact on the complexity of the problem to be solved and the task to be performed in construction planning and scheduling, and an accurate understanding of project objectives, specifications, and constraints is necessary before the definition of the scope of the target project. The agent refers to the entity that observes states, takes actions, and receives rewards in the target project, and it can be conceived as a building, a tower crane, and so on. Depending on the problem to be solved and the task to be performed in construction planning and scheduling, the agent needs to be defined with different levels of autonomy. The state refers to the situation of the target project that the agent observes at a given time step, and it can be conceived as the progress of a building, the direction of a tower crane, and so on. Since the state is typically represented as an array of values that correspond to specific aspects of the target project, it should be concise and informative so that the agent can effectively observe from the target project. The action refers to the prediction or decision that the agent makes to interact with the target project at a given time step, and it can be conceived as the next construction activity in a building, the next construction resource to be transported by a tower crane, and so on. The space of actions determines the range of possible predictions and decisions that the agent can make, and actions can be represented as discrete choices, such as the number of workers for a construction activity, or continuous values, such as the velocity of a tower crane for transporting a construction resource. The reward refers to the feedback that the agent receives about the desirability of the action which it took at a given time step in the target project, and it can be conceived as the cost of a construction activity, the transportation time of a construction resource, and so on. The well-defined reward should provide a distinct feedback to the agent for the corresponding action.

Situation 1 with reinforcement learning enables the agent to learn from scratch without additional intervention, which offers several benefits listed as follows (Table 1) [22][38][39]. First, it can be applied to a wide range of construction problems and tasks with the high-dimensional space of states and actions, making the agent to learn a policy in a multiplex environment that conforms to building and infrastructure projects. Also, the agent can be allowed to explore the target project to discover new construction strategies and solutions, facilitating a more creative and adaptive prediction or decision making process in construction planning and scheduling. Furthermore, the agent can be enabled to optimize construction strategies and solutions in real time, which is well suited for the dynamic and uncertain environment of construction sites and tasks.

On the other hand, there are some limitations to Situation 1 with reinforcement learning (Table 1) [22][40][41]. Since the agent needs to learn a policy by trial and error, it usually requires a large number of interactions with the target project when construction problems and tasks are complex, which may be time-consuming in construction planning and scheduling. Moreover, it lacks supervised feedback during training due to absence of labeled construction data, and therefore requires significant computational time and effort to exploit and explore, resulting in potentially suboptimal construction strategies and solutions.

3.2. Situation 2 with imitation learning

Situation 2 with imitation learning is divided into two main parts. In the first part, the project team demonstrates how to perform a task by observing the target project and taking actions in the target project; and in the second part, the agent imitates these demonstrations to learn a policy based on the knowledge where the project team performs the task. There are two main steps to be executed in the first part. First, the information about the state of the target project, the corresponding action taken by the project team, and the resulting reward is collected, and relevant features from the information are extracted and used as inputs to train a model with the mapping between states and actions to imitate the behavior of the project team. Then, the model is trained using the features prepared and is evaluated with the metrics that measure how well the model imitates, and the trained model as the source of knowledge is used for the learning of the agent once it is deemed satisfactory. The second part is similar to the process of reinforcement learning. The main difference is that the trained model from the first part is updated with new information about the simulation where the agent performs the task.

Situation 2 with imitation learning allows the agent to learn from human expert demonstrations by leveraging the expertise of the project team, and there are several benefits listed as follows (Table 1) [28][42]. First, it not only reduces the training time required for the agent to learn a policy and potentially enables faster construction planning and scheduling, but also reaches a better performance than random exploration and ensures a more reliable prediction or decision making process in construction planning and scheduling. Next, since it is based on the demonstration of the project team, the trained model is more interpretable, enhancing the trust and acceptance of construction strategies and solutions.

In addition, it can provide a cost-effective way for construction planning and scheduling to save computational resources by reducing the amount of trial and error during training.

However, Situation 2 with imitation learning also has some limitations (Table 1) [28][43]. The performance of the trained model is sensitive to the demonstration of the project team. Since the behavior of the project team is easily impacted by various factors such as preferences and biases, and usually, it is not possible to cover all states and actions, the trained model may not be able to generalize well, and its adaptability is limited sometimes in construction planning and scheduling. Furthermore, in building and infrastructure projects, it is not always readily available to obtain labeled demonstration data, especially for complex construction sites and tasks, which may become an obstacle in construction planning and scheduling.

3.3. Situation 3 with transfer learning

Situation 3 with transfer learning is divided into two main parts. In the first part, the source project (i.e., other projects) has demonstrated how to perform a different but related task; and in the second part, the agent learns a policy based on the transferred knowledge where the source project performs the task for the target project. There are two main steps to be executed in the first part. First, the information about the state of the source project, the corresponding action taken by the source project, and the resulting reward has been used to train a model, and this trained model is a desired neural network architecture depending on the problem to be solved and the task to be performed. Then, relevant features extracted from the trained model (e.g., one or more layers of the neural network) are transferred as the source of knowledge for the learning of the agent in the target project. The second part is similar to the process of reinforcement learning. The main difference is that the model of the target project is built on relevant features from the first part and fine-tuned with new information about the simulation where the agent performs the task.

Situation 3 with transfer learning allows the agent to learn a different but related source task by leveraging the experience of other projects, offering several benefits listed as follows (Table 1) [33][44][45]. First, it enables the knowledge learned from other projects to be transferred to the target project, even if construction problems and tasks are not exactly the same, which significantly reduces the amount of construction data required for training and effectively provides a faster way to achieve convergence. Besides, it can give a favorable starting point for the agent to learn a policy by initializing the model of the target project with weights from the trained model of other projects, leading to a good level of accuracy in construction planning and scheduling.

Although Situation 3 with transfer learning can help take advantage of the experience of other projects, it also comes with some limitations (Table 1) [33][46][47]. The effectiveness of the trained model depends on the relevance and common feature of source and target construction problems and tasks as well as the availability and completeness of project information, and it is potentially harmful for the performance of transfer and even results in a negative transfer effect in construction planning and scheduling when the requirements are not met. Additionally, if the knowledge learned from other projects is too specific towards the source construction problem and task, the trained model may overfit, and its generalization and adaptability can be adversely impacted in construction planning and scheduling.

4. Conclusions and outlook

Construction planning and scheduling are one of the most important elements in building and infrastructure project management, which significantly affect various aspects including cost, time, safety, and quality. To improve the accuracy and automation of construction planning and scheduling, various tools, techniques, algorithms, and models have been used for this process. However, due to the multiplex, evolving, and unstructured characteristics of sites and tasks, construction planning and scheduling cannot be conducted well, which is particularly obvious during the execution phase of building and infrastructure projects. With the development of artificial intelligence in recent years, machine learning that is able to deal with complex, dynamic, and uncertain things shows the potential to assist with that problem. Therefore, this study selects reinforcement learning, imitation learning, and transfer learning that can be suitable and play a significant role in construction planning and scheduling, establishes a framework consisting of three situations for structuring and standardizing the application of these three machine learning methods, and discusses their respective benefits and limitations. With the proposed framework, application effectiveness and efficiency could be enhanced and application clarity and repeatability cloud be promoted. In future work, the construction planning and scheduling models with reinforcement learning, imitation learning, and transfer learning for specific application areas will be created, respectively, and their capabilities and performance will be verified and compared with case studies.

Table 1. Benefits and limitations of three situations with machine learning for construction planning and scheduling.

Situations with machine learning	Benefits	Limitations
Situation 1 with reinforcement learning	• Applicable to wide and high-dimensional construction problems and tasks • Beneficial to a more creative and adaptive construction prediction or decision making process • Suited for the dynamic and uncertain environment of construction sites and tasks	• May be time-consuming in construction planning and scheduling • Resulting in potentially suboptimal construction strategies and solutions
Situation 2 with imitation learning	• Potentially enabling faster construction planning and scheduling and ensuring a more reliable construction prediction or decision making process • Enhancing the trust and acceptance of construction strategies and solutions • Providing a cost-effective way for construction planning and scheduling to save computational resources	• May not be able to generalize well and its adaptability is limited sometimes in construction planning and scheduling • Not always readily available to obtain labeled demonstration data especially for complex construction sites and tasks
Situation 3 with transfer learning	• Reducing the amount of construction data required for training and providing a faster way to achieve convergence • Leading to a good level of accuracy in construction planning and scheduling	• Potentially harmful for the performance of transfer and even resulting in a negative transfer effect in construction planning and scheduling • Generalization and adaptability of the knowledge learned from other construction projects may be adversely impacted

References

[1] J. Hinze, “Construction planning and scheduling,” Pearson, 2004, ISBN: 0132473984.
[2] S. A. Mubarak, “Construction project scheduling and control,” John Wiley & Sons, 2015, ISBN: 1118846001.
[3] A. Baldwin and D. Bordoli, “A handbook for construction planning and scheduling,” John Wiley & Sons, 2014, ISBN: 9780470670323.
[4] M. T. Callahan, D. G. Quackenbush, and J. E. Rowings, “Construction project scheduling,” National Academies of Sciences, Engineering, and Medicine, 1992, ISBN: 0070097011.
[5] J. M. Wilson, “Gantt charts: A centenary appreciation,” European Journal of Operational Research, 149(2), 430-437, 2003, doi: 10.1016/S0377-2217(02)00769-5.
[6] T. Zhao and C. L. Tseng, “A note on activity floats in activity-on-arrow networks,” Journal of the Operational Research Society, 54(12), 1296-1299, 2003, doi: 10.1057/palgrave.jors.2601636.
[7] K. Neumann and C. Schwindt, “Activity-on-node networks with minimal and maximal time lags and their application to make-to-order production,” Operations-Research-Spektrum, 19, 205-217, 1997, doi: 10.1007/BF01545589.
[8] Q. Chen, B. García de Soto, and B. T. Adey, “Construction automation: Research areas, industry concerns and suggestions for advancement,” Automation in Construction, 94, 22-38, 2018, doi: 10.1016/j.autcon.2018.05.028.
[9] M. J. Liberatore, B. Pollack-Johnson, and C. A. Smith, “Project management in construction: Software use and research directions,” Journal of Construction Engineering and Management, 127(2), 101-107, 2001, doi: 10.1061/(ASCE)0733-9364(2001)127:2(101).

[10] B. García de Soto, A. Rosarius, J. Rieger, Q. Chen, and B. T. Adey, “Using a Tabu-search algorithm and 4D models to improve construction project schedules,” Procedia Engineering, 196, 698-705, 2017, doi: 10.1016/j.proeng.2017.07.236.
[11] K. Wu and B. García de Soto, “Spatiotemporal modeling of lifting task scheduling for tower cranes with a tabu search and 4-D simulation,” Frontiers in Built Environment, 6, 79, 2020, doi: 10.3389/fbuil.2020.00079.
[12] J. M. Antill and R. W. Woodhead, “Critical path methods in construction practice,” John Wiley & Sons, 1991, ISBN: 978-0-471-62057-0.
[13] W. D. Cottrell, “Simplified program evaluation and review technique (PERT),” Journal of Construction Engineering and Management, 125(1), 16-22, 1999, doi: 10.1061/(ASCE)0733-9364(1999)125:1(16).
[14] S. M. Easa, “Resource leveling in construction by optimization,” Journal of Construction Engineering and Management, 115(2), 302-316, 1989, doi: 10.1061/(ASCE)0733-9364(1989)115:2(302).
[15] M. H. Elwany, I. E. Korish, M. A. Barakat, and S. M. Hafez, “Resource smoothening in repetitive projects,” Computers & Industrial Engineering, 35(3-4), 415-418, 1998, doi: 10.1016/S0360-8352(98)00122-3.
[16] R. A. Russell, “A comparison of heuristics for scheduling projects with cash flows and resource restrictions,” Management Science, 32(10), 1291-1300, 1986, doi: 10.1287/mnsc.32.10.1291.
[17] A. Jiang and Y. Zhu, “A multi-stage approach to time-cost trade-off analysis using mathematical programming,” International Journal of Construction Management, 10(3), 13-27, 2010, doi: 10.1080/15623599.2010.10773147.
[18] T. W. Liao, P. J. Egbelu, B. R. Sarker, and S. S. Leu, “Metaheuristics for project and construction management – A state-of-the-art review,” Automation in Construction, 20(5), 491-505, 2011, doi: 10.1016/j.autcon.2010.12.006.
[19] T. M. Mitchell, “Machine learning,” McGraw-Hill Education, 1997, ISBN: 0070428077.
[20] N. S. Kedir, S. Somi, A. R. Fayek, and P. H. Nguyen, “Hybridization of reinforcement learning and agent-based modeling to optimize construction planning and scheduling,” Automation in Construction, 142, 104498, 2022, doi: 10.1016/j.autcon.2022.104498.
[21] S. Cho and S. Han, “Reinforcement learning-based simulation and automation for tower crane 3D lift planning,” Automation in Construction, 144, 104620, 2022, doi: 10.1016/j.autcon.2022.104620.
[22] L. P. Kaelbling, M. L. Littman, and A. W. Moore, “Reinforcement learning: A survey,” Journal of Artificial Intelligence Research, 4, 237-285, 1996, doi: 10.1613/jair.301.
[23] J. Gläscher, N. Daw, P. Dayan, and J. P. O'Doherty, “States versus rewards: Dissociable neural prediction error signals underlying model-based and model-free reinforcement learning,” Neuron, 66(4), 585-595, 2010, doi: 10.1016/j.neuron.2010.04.016.
[24] M. Hausknecht and P. Stone, “On-policy vs. off-policy updates for deep reinforcement learning,” Deep Reinforcement Learning: Frontiers and Challenges, IJCAI 2016 Workshop, July, 2016, http://www.cs.utexas.edu/users/ai-lab?hausknecht:deeprl16.
[25] O. Nachum, M. Norouzi, K. Xu, and D. Schuurmans, “Bridging the gap between value and policy based reinforcement learning,” 31st Conference on Neural Information Processing Systems (NIPS 2017), 2017, doi: 10.48550/arXiv.1702.08892.
[26] J. Schrittwieser, T. Hubert, A. Mandhane, M. Barekatain, I. Antonoglou, and D. Silver, “Online and offline reinforcement learning by planning with a learned model,” Advances in Neural Information Processing Systems, 34, 27580-27591, 2021, doi: 10.48550/arXiv.2104.06294.
[27] S. Gronauer and K. Diepold, “Multi-agent deep reinforcement learning: A survey,” Artificial Intelligence Review, 1-49, 2022, doi: 10.1007/s10462-021-09996-w.
[28] A. Hussein, M. M. Gaber, E. Elyan, and C. Jayne, “Imitation learning: A survey of learning methods,” ACM Computing Surveys (CSUR), 50(2), 1-35, 2017, doi: 10.1145/3054912.
[29] F. Torabi, G. Warnell, and P. Stone, “Behavioral cloning from observation,” 27th International Joint Conference on Artificial Intelligence (IJCAI 2018), July, 2018, doi: 10.48550/arXiv.1805.01954.
[30] A. Attia and S. Dayan, “Global overview of imitation learning,” arXiv preprint arXiv:1801.06503, 2018, doi: 10.48550/arXiv.1801.06503.
[31] A. Y. Ng and S. Russell, “Algorithms for inverse reinforcement learning,” 27th International Conference on Machine Learning (ICML 2000), June, 2000, http://www.datascienceassn.org/sites/default/files/Algorithms%20for%20Inverse%20Reinforcement%20Learning.pdf.
[32] J. Ho and S. Ermon, “Generative adversarial imitation learning,” Advances in Neural Information Processing Systems, 29, 2016, doi: 10.48550/arXiv.1606.03476.
[33] S. J. Pan and Q. Yang, “A survey on transfer learning,” IEEE Transactions on Knowledge and Data Engineering, 22(10), 1345-135, 2010, doi: 10.1109/TKDE.2009.191.
[34] W. M. Kouw and M. Loog, “An introduction to domain adaptation and transfer learning,” arXiv preprint arXiv:1812.11806, 2018, doi: 10.48550/arXiv.1812.11806.
[35] Y. Zhang and Q. Yang, “An overview of multi-task learning,” National Science Review, 5(1), 30-43, 2018, doi: 10.1093/nsr/nwx105.
[36] S. Desai, M. Mattheakis, H. Joy, P. Protopapas, and S. Roberts, “One-shot transfer learning of physics-informed neural networks,” arXiv preprint arXiv:2110.11286, 2021, doi: 10.48550/arXiv.2110.11286.
[37] L. Huang, H. Ji, K. Cho, and C. R. Voss, “Zero-shot transfer learning for event extraction,” arXiv preprint arXiv:1707.01066, 2017, doi: 10.48550/arXiv.1707.01066.
[38] Y. Li, “Deep reinforcement learning: An overview,” arXiv preprint arXiv:1701.07274, 2017, doi: 10.48550/arXiv.1701.07274.
[39] K. Arulkumaran, M. P. Deisenroth, M. Brundage, and A. A. Bharath, “Deep reinforcement learning: A brief survey,” IEEE Signal Processing Magazine, 34(6), 26-38, 2017, doi: 10.1109/MSP.2017.2743240.
[40] M. Botvinick, S. Ritter, J. X. Wang, Z. Kurth-Nelson, C. Blundell, and D. Hassabis, “Reinforcement learning, fast and slow,” Trends in Cognitive Sciences, 23(5), 408-422, 2019, doi: 10.1016/j.tics.2019.02.006.
[41] T. T. Nguyen, N. D. Nguyen, and S. Nahavandi, “Deep reinforcement learning for multiagent systems: A review of challenges, solutions, and applications,” IEEE Transactions on Cybernetics, 50(9), 3826-3839, 2020, doi: 10.1109/TCYB.2020.2977374.

[42] B. Fang, S. Jia, D. Guo, M. Xu, S. Wen, and F. Sun, "Survey of imitation learning for robotic manipulation," International Journal of Intelligent Robotics and Applications, 3, 362-369, 2019, doi: 10.1007/s41315-019-00103-5.
[43] B. Zheng, S. Verma, J. Zhou, I. W. Tsang, and F. Chen, "Imitation learning: Progress, taxonomies and challenges," IEEE Transactions on Neural Networks and Learning Systems, 1-16, 2022, doi: 10.48550/arXiv.2106.12177.
[44] K. Weiss, T. M. Khoshgoftaar, and D. Wang, "A survey of transfer learning," Journal of Big data, 3(1), 1-40, 2016, doi: 10.1186/s40537-016-0043-6.
[45] H. Liang, W. Fu, and F. Yi, "A survey of recent advances in transfer learning," 19th International Conference on Communication Technology, 1516-1523, 2019, doi: 10.1109/ICCT46805.2019.8947072.
[46] C. Tan, F. Sun, T. Kong, W. Zhang, C. Yang, and C. Liu, "A survey on deep transfer learning," 27th International Conference on Artificial Neural Networks, 270-279, 2018, doi: 10.48550/arXiv.1808.01974.
[47] F. Zhuang, Z. Qi, K. Duan, D. Xi, Y. Zhu, H. Zhu, H. Xiong, and Q. He, "A comprehensive survey on transfer learning," Proceedings of the IEEE, 109(1), 43-76, 2020, doi: 10.48550/arXiv.1911.02685.

ACTIVITIES OF RESTRICTED DURATION IN NETWORK TIME MODELS OF CONTRUCTION PROJECTS

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Abstract

Activities of fixed-, flexible-, intermittent-, distributable-, and unknown duration in general network time models are discussed in the paper on basis of preset lower and upper bounds on their time extent. After a short historical review, we discuss the theoretical background and we introduce a modified Floyd-Warshall algorithm to calculate a generalized network time model (GTM) highlighting differences of well-known techniques of PERT, CPM, MPM and PDM. Finally, we publish a small construction problem to demonstrate practical application and modelling activities of these kinds.

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Keywords: construction management, graph techniques, network techniques, scheduling.

1. Introduction

Computer aided management, dynamic time models, anticipating consequences of any changes in planned performance, being informed on actual progression are unceasing expectations and eternal challenges of modern project management. CPM, PERT, MPM, PDM are well-known acronyms of techniques inseparable of evolution of computers and developed to ease the work of experts responsible for time management of projects on various fields of human life and of economy. Principles of all before-mentioned techniques can be derived from a primal-dual pair of problems in applied mathematics, namely, the problem of finding the Longest Path(s) between two distinguished nodes of a weighted directed graph and the problem of constructing a Minimum Potentials' system having limitations (lower and/or upper bounds) on pair-wise differences of its elements. Algorithms to solve these problems are usually based on some kind of labelling techniques (such as Dijkstra's [1] for finding the shortest path(s)), to construct the potentials' system first, that provides basis for identifying the longest path(s) [4][6][8][9]. The logic works in a reversed way too. Identifying the longest path(s) between a distinguished pair (or all pairs) of nodes of the graph first, the system of minimum potentials' can be constructed [11] too. It is common in both approaches that weights of directed edges – that is, lower bounds on pair-wise differences of potentials – are input values for the calculations while potentials' system is an expected output.

Construction management frequently faces situations that time extent of some efforts (activities or sub-projects) are unknown or can be estimated with significant uncertainty or it is not expedient to set them in advance but let them be adjusted to more certain components of the project.

Subject of our research is the ways and tools of integrating these kinds of efforts (activities of flexible duration, activities broken by idle times, activities performed by parallel teams, and activities of unknown duration) in dynamic time model of construction projects.

2. Historical review

At first steps of developing modern computer aided project management techniques Kelley and Walker [6] developed a time model on a particular structure of data that can be demonstrated by a directed weighted graph with one originating node, with one terminal node, with no circular references, and with non-negative weights assigned to the edges. The structure was referred as "network". By evolution of computer techniques all before-mentioned restriction on data structure became omissible but the only one that is essential for a valid mathematical solution: no positive circular references allowed. They used AOA (Activity-On-Arrow) correspondence of project time elements and their in-graph representatives. Nodes are establishing direct links between preceding activities (represented by arrows entering the nodes) and succeeding activities (represented by arrows leaving the nodes). Weights of arrows are input values for calculations. The aim is to determine minimum overall timespan of the project, that is, to calculate the length of the longest by-arrow sequence(s) of directed edges (referred as Critical Path) between the originating node and terminating node of the graph (CPM^{time} model).

Based on fast computer-aided calculations and involving time-cost trade-off of project components focus of time planning could be set on finding an optimal time policy for shortening the overall timespan of the project in a cost-effective way. Method of optimization was derived back to recursive calculations of the network (network time analysis) and changing the input values (weights of activities) step-by-step in a purposeful way for each succeeding recalculation (CPM^{cost} model). Acceptable ranges of durations were set by upper bounds (normal times) and lower bounds (crash times) while the trade-off functions (cost slopes) between them was assumed to be linear.

Weights (estimates on activity durations) were also in focus of examinations in technique developed for US Navy at the end of fifties of the last Century referred as Program Evaluation and Review Technique (PERT) [7]. Uncertainty of estimating time extent of activities (sub-projects) was integrated in the model on a probabilistic basis (assuming Beta distribution, based on triplets of time estimates for each activity: optimistic, realistic, and pessimistic ones) but the CPM^{time} typed network time analysis was derived back to a single calculation with deterministic values (expected durations).

AOA typed correspondence of project elements and their graph representatives proved to be insufficient to model mutual dependencies of activities that can be overlapped in time. Reversed correspondence, that is, nodes representing activities of fixed duration and weighted arrows representing technological dependencies, provided tools for modelling any relative time positions of related activities. (Activity-On-Node (AON) correspondence) Assuming linear progression of each activity Fondahl [3] and Roy [9][10] proposed four basic types of relations (Finish-to-Finish, Finish-to-Start, Start-to-Finish, Start-to-Start) to guide relative time positions of succeeding activities. But special combination of these relations together with fixed durations of activities can result in a paradox of durations [5][12][15] and imply negative weights and circular references in the graph model [13].

Vattai and Mályusz [11] approached the network time scheduling problem in a reversed way. Find the longest path(s) and assign time potentials for the individual project components along them. They adapted the well-known Floy-Warshall algorithm [2][14] to determine all-pairs longest path(s) in the weighted directed graph and discarded all restrictions on the graph structure. They recalled the early AOA correspondence of project components and their graph representatives in a generalized way. Arrows are representing time extents (regardless of their technical meaning – activity duration or lead or lag time) and nodes are representing time positions (regardless of their technical meaning – deadline, milestone, or direct link). Applying various bounding schemes on acceptable ranges of activity durations, appropriate values of them can also be a partial output of (and not input for) network time analysis.

This paper aims at discussing practice and proper use of bounding schemes on activity durations to promote modelling some scheduling challenges typical in Construction Management.

3. Introducing lower and upper bounds on duration of activities

Activity durations are “bounded” in all network techniques some-how. CPM, PERT, MPM, PDM imply activities of fixed duration only and acceptable increments or delay(s) of their timing is handled by series of float- or slack values (Total Float, Free Float, Independent Float for activities, Slack for events). The novelty of proposed General Time Model (GTM) is that actual values of durations are defined by ranges bounded from down, or from up, or both, or neither – instead of fixed discrete values – while the model keeps calculable. Below we review basic types of activities of limited duration and their application in context of construction projects. Figure 1 shows proposed shields for activities indicating their bounding schemes and arrangement of time data (Early Start, Early Finish, Duration minimum, Duration, Duration maximum, Late Start, Late Finish) within them. We also introduce a denotation “CR” for a special kind of duplex relation, namely, for Finish-to-Finish (FF) and Start-to-Start (SS) relation together, with the same bounding value for defining technological breaks (succession times) between succeeding activities overlapped in time – regardless of their actual duration. (Graphics below have been created by computer application “GRProject” developed for educational purposes at BUTE DCT&M 2022-2023 to demonstrate different types of network techniques, such as CPM, MPM and GTM.)

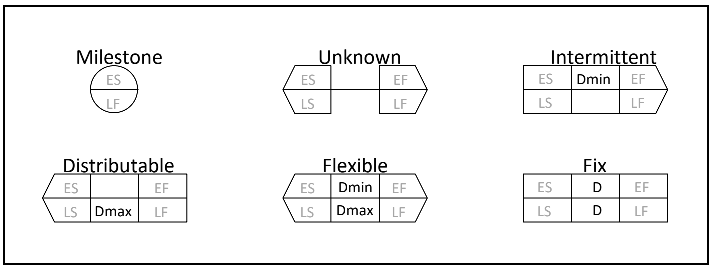

Figure 1. Representation- and arrangement of time data in shields of activities of variously limited duration in app. “GRProject”

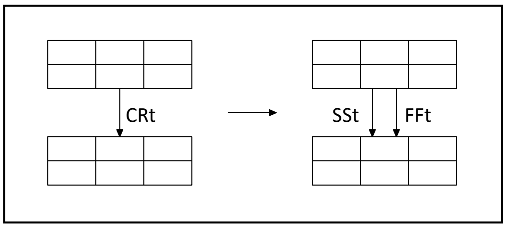

Figure 2. Introducing relation CR to represent technological break between succeeding activities overlapped in time

3.1. Milestone

An “activity” duration of which is fixed to value “zero” (D_{min}=D=D_{max}=0) and is frequently referred as event or milestone. It has no time extent but time position. Mostly used to indicate special states or fulfilment of some expectations, achieving an intermediate- or ultimate target, or simply indicating a common deadline for some parallelly ongoing efforts. Transition of events and activities is an inherent question in all network techniques since duration of activities can be approached as elapsing time between two events (between start and finish – see CPM and PERT activities) and events can be handled as zero-duration activities (see CPM dummy activities and MPM milestones).

3.2. Activity of unknown duration

Also referred as hammock activities [4]. Most of scheduling software applications available on the market (such as Microsoft Project, Gantt Project etc.) are – as considered – provided with tools to integrate activities of this kind in network time models (usually as summary activities) but the comparison is incorrect. In before mentioned applications time positions (starting and ending times) of these activities are not integrated in the network model but are projected from results of network time analysis. The need for integrating activities of this kind in the network time model emerges when availability of some resources assigned to them is essential consideration of the project. Such as: tower cranes, dewatering pumps, guarding-, occupying (renting) public areas etc. We can define the first time we need them during execution of the project, and we can define the last time too. Actual period of need for them is determined by other activities in the time model. Their improper use can lead to a strange situation – as an outcome of network time analysis – that the activity should be finished before it has been started (?!). It can be a true blunder – or can be an indication that progression of the activity (sub-project) would be better scheduled in opposing direction than it had been assumed in advance. (This later is easier to interpret at linear structures such as bridges, tunnels, retaining walls, transmission lines, highways etc.)

3.3. Intermittent activity

Activity performance of which can be paused and restarted any times as needed in the execution period. Its minimum time extent can be estimated accurately but idle times are allowable during its completion. The range of acceptable duration is set by a lower bound only ($D_{min} \le D$) based on the estimated time needed to perform the whole activity without any break. Appropriate range of idle times and the whole timespan to complete the activity can be derived from output of network time analysis. Losses due to idle times in periods of on-site works are essential problems. Assigning alternative jobs for the teams performing these activities can be an effective way of reducing them. Such as: formwork in, formwork out or temporary support in, temporary support out at concrete works of structures like retaining walls, bridges, tunnels, high-rise buildings, etc. Workers are performing more jobs during the execution period in an alternating way ("alternating team").

Figure 3 shows an example of applying intermittent activity and explains principles of turning primary results of time analysis (e.g.: early starts, early finishes) to detailed schedule of its performance. (Idle times are spread in time evenly.)

Relations 1-4 below can be used to prepare a detailed schedule of intermittent activities.

$$D = EF - ES \quad (1)$$

$$n = \min \{ D_{min} ; D - D_{min} \} \quad (2)$$

$$S = \frac{D}{n} \quad (3)$$

$$D_s = \frac{D_{min}}{n} \quad (4)$$

Where: *D* = scheduled timespan (*Duration*) to complete the activity
ES, *EF* = *Early Start* and *Early Finish* of the activity, output from network time analysis
n = number of periods of breakless performances
S = delay (*Step*) time for starting succeeding period of breakless performance
D_s = *Duration* of performing one breakless period

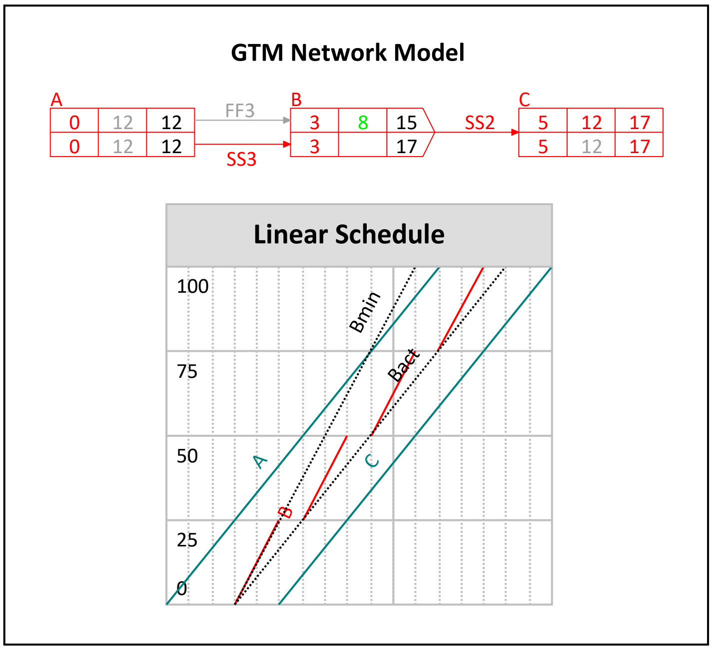

Figure 3. Scheduling intermittent performance of activity "B". ($D_{min}=D_{Bmin}=8$; $D=D_{Bact}=12$; $n=4$; $S=3$; $D_s=2$)

3.4. Distributable activity

A strange and to be handled carefully type of activities – bot not far from construction reality. Significant expensive and unacceptably slow at construction site, and usually "accelerated" by mobilizing more parallel teams and/or machines to perform them. The number of mobilized teams/machines are usually set in advance, but – in an accepted range – can be derived from results of time analysis of the network time model. Range of acceptable duration is set by an upper bound ($D \leq D_{max}$), based on the estimated time needed to perform the whole activity by one team/machine. Since the minimum side is not set in advance, in case of uncarefully constructed time model it may occur that the activity should be finished before it has been started(?!) – that is an evident mistake. So, both the start and the finish of these activities should be guided properly by the related activities in the time model.

Figure 4 shows an example of applying parallel teams and explains principles of turning primary results of time analysis (e.g.: early starts, early finishes) to detailed schedule of their performance.

Relations 5-9 below can be used to prepare a detailed schedule for parallel teams.

$$D = EF - ES \tag{5}$$

$$C = \left\lceil \frac{D_{max}}{D} \right\rceil \tag{6}$$

$$n = \frac{C \cdot (D_{max} - D)}{C \cdot D - D_{max}} + 1 \tag{7}$$

$$S = \frac{D}{n + C - 1} \tag{8}$$

$$D_s = \frac{D_{max}}{n} \tag{9}$$

Where: *D* = scheduled time frame (*Duration*) to perform the activity
ES, *EF* = *Early Start* and *Early Finish* of the activity, output from network time analysis
C = number of parallel teams (*Capacity*) to be mobilized to perform the activity (rounded up)
n = number of sections the activity is to be distributed (segmented) among
S = delay (*Step*) time for succeeding parallel teams to start their sections
D_s = *Duration* of performing the activity by one team in one section

Remark: relations 5 - 9 are applicable if n>2 and $D_{max} \neq k \cdot D$ where k is an integer

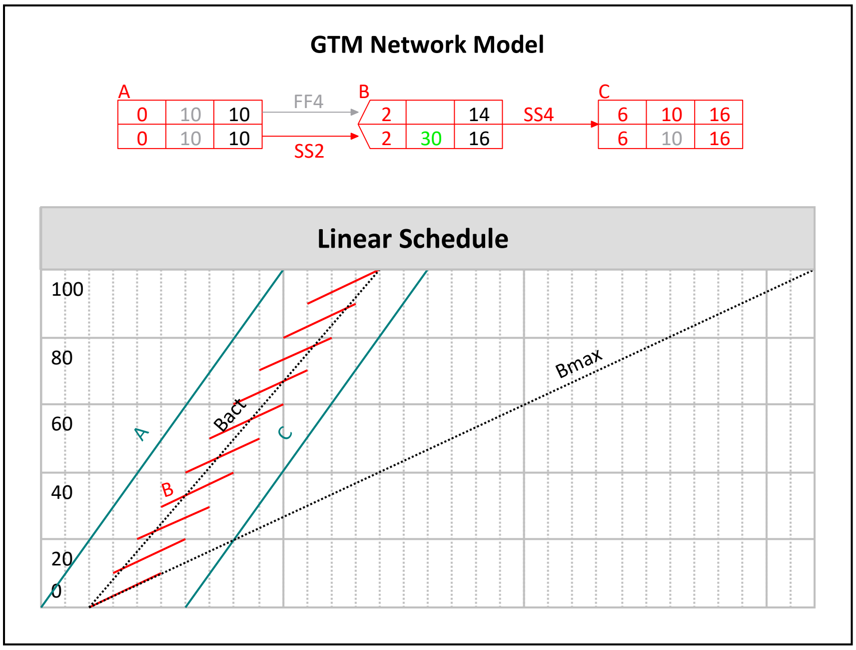

Figure 4. Applying 3 parallel teams to perform activity "B". (D_{max}=D_{Bmax}=30; D=D_{Bact}=12; C=3; n=10; S=1; D_s=3)

3.5. Flexible activity

Also referred as stretchable activity. Scheduled or expected duration of the activity is restricted to an accepted range set by a lower and an upper bound ($D_{min} \leq D \leq D_{max}$). Though the rest of the activities in construction practice is of this type, most of the network techniques do not provide a tool to involve them in the time model. Assigning ranges of acceptable duration values for the individual activities makes possible to determine the best fitting durations by the network time analysis itself [8]. That is: actual durations of activities are expected outputs of network time analysis.

3.6. Activity of fixed duration

Scheduled or expected duration of the activity is well known and its technical content is specified exactly. Both the lower- and the upper bound of the time extent equals to the expected duration ($D_{min}=D=D_{max}$). In MPM and PDM techniques it is the basic type of activities, and their durations are pre-set input values of network time analysis. Due to the manifold relations allowed in MPM/PDM techniques consequences of any changes of duration of critical activities of this kind can be forecasted via thorough analyses of their dominant relations [5][12][15].

4. Network time analysis

In a General Time Model relative time position of each project component (activity or milestone) is defined by a pair of time potentials – one for its start (π_s) and one for its finish (π_f). Relations 10-11 are for calculating indices of time potentials of a project component *m*.

$$s = 2 \cdot m - 1 \qquad \text{(start potential)} \qquad (10)$$

$$f = 2 \cdot m \qquad \text{(finish potential)} \qquad (11)$$

All restrictions on differences of time potentials are transformed to a single or to a duplex of lower bound typed limitation(s) (See relations 12-14).

$$\pi_j - \pi_i \geq \tau_{ij} \qquad \text{(lower bound)} \qquad (12)$$

$$\pi_j - \pi_i \leq \tau_{ij} \quad \equiv \quad \pi_i - \pi_j \geq -\tau_{ij} \qquad \text{(upper bound)} \qquad (13)$$

$$\pi_j - \pi_i = \tau_{ij} \quad \equiv \quad (\pi_j - \pi_i \geq \tau_{ij}) \cup (\pi_i - \pi_j \geq -\tau_{ij}) \qquad \text{(fixed value)} \qquad (14)$$

Where: π_i and π_j are related time potentials in potentials' system
τ_{ij} is the bounding value set on difference of time potentials π_i and π_j

Potentials are assigned to nodes of the graph, and restriction(s) on pair-wise differences of potentials are represented by weighted directed edges – where weights are the bounding values themselves.

A modified Floyd-Warshall algorithm can be used to prepare transitive closure ($\underline{\underline{A}}^n$) of the structure matrix ($\underline{\underline{A}}^0$) of the weighted directed graph. Cells of the former contains length of the longest path(s) (if any) between all pairs of nodes. Figure 5 shows a Delphi routine for the modified Floyd-Warshall algorithm.

```
{ Preparing (A0 ) matrix }
for i:=1 to n do
   for j:=1 to n do begin
      a[i,j]:= w[i,j]*;
      { … }
   end;

*a[i,j]:=w[i,j], if (i,j)∈E;
 a[i,j]:=M      otherwise
```

```
{ Preparing transitive closure (An) of structure matrix (A0) }
for k:=1 to n do              {outer cycle, selecting node k as transitive node}
   for i:=1 to n do                       {inner cycles, tabular calculations}
      for j:=1 to n do
         if a[i,k]+a[k,j]>a[i,j] then begin            {conditional exchange…}
            a[i,j]:=a[i,k]+a[k,j];                     { ... of calculated values }
            { … }
         end;
```

Figure 5. Delphi routines of modified Floyd-Warshall algorithm. a[i,j] represents calculated value in i,j cell of the distance matrix. w[i,j] represents weight of directed edge between nodes i and j. E is for set of edges of the graph. M is a marker value representing still not discovered connection in the given relation. Running indices are for rows (i), columns (j) and recursions (k). n=2·m.

Early time potentials (π_j) are defined as length of longest path(s) between the starting node(s) and the actual node of the graph. Late time potentials (π'_i) are defined as length of longest path(s) between the actual node and the finish node(s) of the graph. (See relations 15-17)

$$\pi_j = \max\{0, \max_i a_{ij}^n\} \qquad \forall j \qquad (15)$$

$$\Pi = \max_j \pi_j = \max_{ij} a_{ij}^n \qquad (16)$$

$$\pi'_i = \min\{\Pi, \min_j(\Pi - a_{ij}^n)\} \qquad \forall i \qquad (17)$$

For more details see Vattai 2016 [11].

5. Sample project

To demonstrate application of above-mentioned activities here we cite some details of a small project to be elaborated by students of civil engineering studies at Budapest University of Technology and Economics. The job is to prepare time and resource estimates of building a RC retaining wall at a fictive highway correctional project. In our example height of the wall is 4 m and length of it is 400 m.

According to the assignment: time and resource estimates are to be based on calculations including quantities, standards/outputs of performances and available capacities. Quantity of formwork can cover maximum 100 m long a section of the structure. Progressions of works are to be synchronized in time as much as can be.

Figure 6 shows a schematic cross-section of the structure. GTM network time model of the project can be seen in Figure 7. Detailed schedule of works is presented in form of a linear schedule in Figure 8.

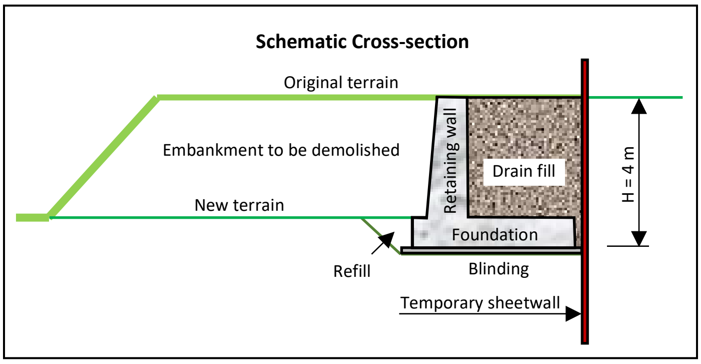

Figure 6. Schematic cross-section of the wall

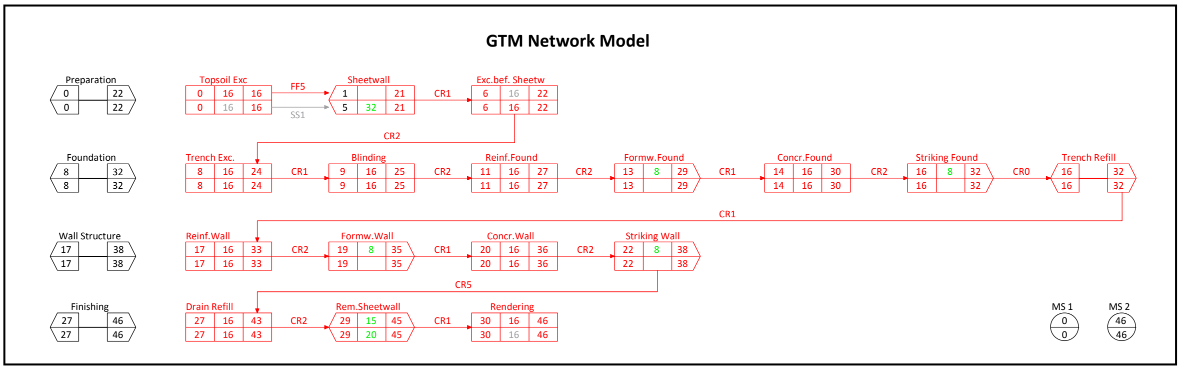

Figure 7. GTM time model of works. (Summary activities and milestones are separated from the core of the model.)

ID	Name	Duration Minimum	Duration Maximum	Scheduled Duration
1	SITE PREPARATION			22
2	Excavating topsoil	16	16	16
3	Sheetwall piling		32	20
4	Excavation at the sheetwall	16	16	16
5	FOUNDATION WORKS			24
6	Excavating foundation trench	16	16	16
7	Blinding	16	16	16
8	Reinforcing foundation	16	16	16
9	Formworking foundation	8		16
10	Concreting foundation	16	16	16
11	Striking, demolishing formwork	8		16
12	Refilling trench along foundation			16
13	WALL CONSTRUCTION			21
14	Reinforcing the wall	16	16	16
15	Formworking the wall	8		16
16	Concreting the wall	16	16	16
17	Striking, demolishing formwork	8		16
18	FINISHING WORKS			19
19	Drain fill behind the wall	16	16	16
20	Removing sheetwall	15	20	16
21	Rendering along the retaining wall	16	16	16
22	Milestone 1 (Start)	0	0	0
23	Milestone 2 (Finish)	0	0	0

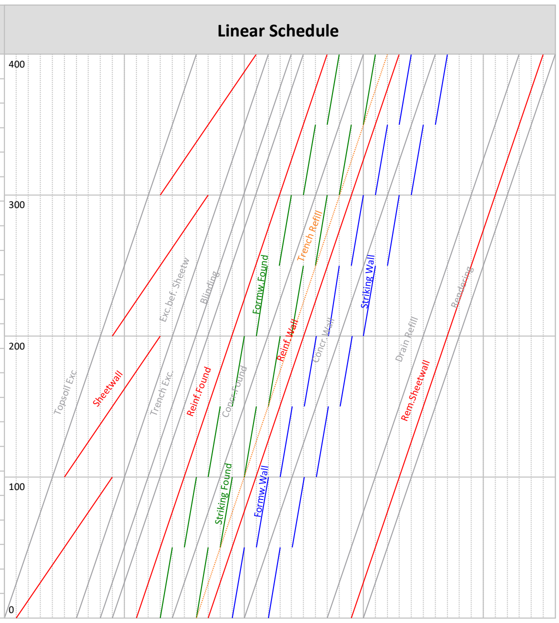

Figure 8. Linear schedule of works based on GTM time model (graphic output from app. "GRProject")

Sheet-wall piling is represented by a distributable activity in the model (ID3 - red lines). Formworks are modelled as alternating jobs for teams performing them (ID9 and ID11 - green lines; ID15 and ID17 - blue lines). Trench refill of small quantity along the foundation is inserted in the model as activity of unknown duration (ID12 – dotted line in ochre). Progression of removing sheet-wall is represented by a flexible activity scheduled duration of which is also an output of GTM time analysis (ID20 - red line). Other jobs are built in the time model as activities of fixed duration (grey progression lines). (Summary activities and milestones are not indicated in the linear schedule.)

6. Conclusions

After a short historical review of network techniques, we introduced a General Time Model applicable to construct network time models including activities ranges of acceptable durations of which are set by lower and/or upper bound values. Via technical examples and via a small theoretical road correctional project we demonstrated their use in context of Construction Industry. We highlighted main differences of traditional network techniques used to develop dynamic time models of different types of projects and we also pointed at the common mathematical background of them. The proposed GTM model is based on calculations of all-pairs longest paths by a modified Floyd-Warshall algorithm. Research is going on to develop even more efficient methods and to overcome disadvantages of admittedly time and memory consuming Floyd-Warshall algorithm, with special consideration of sparse graphs, that is a characteristic feature of network time models typical in construction practice.

6. References

[1] E. W. Dijkstra, "A note on two problems in connexion with graphs," Numerische Mathematik, vol. 1, no. 1, pp. 269–271, Dec. 1959, doi: 10.1007/bf01386390.
[2] R. W. Floyd, "Algorithm 97: Shortest path," Communications of the ACM, vol. 5, no. 6, p. 345, Jun. 1962, doi: 10.1145/367766.368168.
[3] Fondahl, John W., A non-computer approach to the critical path method for the construction industry, Stanford, Calif., Dept. of Civil Engineering, Stanford University, 1962.
[4] M. Hajdu, "Network Scheduling Techniques for Construction Project Management", Nonconvex Optimization and Its Applications, 1997, doi: 10.1007/978-1-4757-5951-8.
[5] M. Hajdu, M. J. Skibniewski, M. Vanhoucke, A. Horvath, and I. Brilakis, "How Many Types of Critical Activities Exist? A Conjecture in Need of Proof," Procedia Engineering, vol. 164, pp. 3–11, 2016, doi: 10.1016/j.proeng.2016.11.585.
[6] J. E. Kelley and M. R. Walker, "Critical-path planning and scheduling," Papers presented at the December 1-3, 1959, eastern joint IRE-AIEE-ACM computer conference on - IRE-AIEE-ACM '59 (Eastern), 1959, doi: 10.1145/1460299.1460318.
[7] D. G. Malcolm, J. H. Roseboom, C. E. Clark, and W. Fazar, "Application of a Technique for Research and Development Program Evaluation," Operations Research, vol. 7, no. 5, pp. 646–669, Oct. 1959, doi: 10.1287/opre.7.5.646.
[8] L. Mályusz and Z. Vattai, "Project scheduling algorithms for construction projects with stretchable activities," IOP Conference Series: Materials Science and Engineering, vol. 1218, no. 1, p. 012043, Jan. 2022, doi: 10.1088/1757-899x/1218/1/012043.
[9] B. Roy, Les problémes d' ordonnancement, Dunod, Paris, 1964
[10] B. Roy and B. Sussmann, Les problémes d' ordonnancement avec contraintes disjonctives, Note DS no 9. bis, SEMA, Montrouge, 1964
[11] Z. A. Vattai, "FLOYD-warshall in Scheduling Open Networks," Procedia Engineering, vol. 164, pp. 106–114, 2016, doi: 10.1016/j.proeng.2016.11.598.
[12] Z. A. Vattai, "'Critical' Terminology – Apropos of a Conjecture," Procedia Engineering, vol. 196, pp. 754–762, 2017, doi: 10.1016/j.proeng.2017.08.004.
[13] Z. A. Vattai and L. Mályusz, "Negative weights in network time model," Frontiers of Engineering Management, vol. 9, no. 2, pp. 268–280, Apr. 2020, doi: 10.1007/s42524-020-0109-1.
[14] S. Warshall, "A Theorem on Boolean Matrices," Journal of the ACM, vol. 9, no. 1, pp. 11–12, Jan. 1962, doi: 10.1145/321105.321107.
[15] J. D. Wiest, "Precedence diagramming method: Some unusual characteristics and their implications for project managers," Journal of Operations Management, vol. 1, no. 3, pp. 121–130, Feb. 1981, doi: 10.1016/0272-6963(81)90015-2.

AN ε-CONSTRAINT METHOD WITH ADAPTIVE MODE ELIMINATION SCHEME FOR MULTI-OBJECTIVE MIXED INTEGER PROGRAMMING

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Abstract

The significance of time-cost trade-off is well recognized for over five decades ever since the development of the critical path method. This trade-off originates from the fact that faster accomplishment of project activities, and thereby the project as a whole, is possible should there be more productive resources assigned. Increasing productivity, on the other hand, typically comes at a cost but possibly helps avoid incurrence of additional overhead and/or penalty expenses. The precise determination of the balance between the planned productivity and the aforesaid costs often poses a tough decision to make by the management. The process of finding the proper combination of execution modes gets particularly complex and computationally expensive for real-scale projects. Accordingly, to help set the proper balance between the time and cost of large projects, an ε-constraint method is presented in this study featuring a clever adaptive mode elimination scheme. The proposed approach involves the iterative optimal solution of the trade-off problem over the feasible project durations. For each project realization, the complexity of the optimization problem is first reduced with the aid of the adaptive mode elimination by discarding the redundant execution mode(s). This study uses mixed integer linear programming for formulation and development of the proposed model and uses a project example borrowed from the literature to experiment its usefulness.

Keywords: ε-constraint method, mixed integer programming, mode elimination, multiobjective optimization, network reduction.

1. Introduction

The main objectives of most projects are completing them on time, within budget, and with high stakeholder satisfaction. In the construction industry, competition among companies often involves offering unique scheduling proposals that result in reasonable profits. Project stakeholders typically aim to complete projects as efficiently as possible to free up resources and gain financial benefits. There are often multiple alternatives available for execution of each project activity in terms of both duration and cost. Many activities can be performed using more efficient construction methods or by allocating additional resources for speeding them up. Decision-makers seek to expedite the project while minimizing extra expenses by finding the best range of alternatives for performing project activities and taking advantage of slack times in the project network. To achieve this, decision-makers strive to find the optimal balance between direct and indirect project costs since on the one hand, reduced project duration leads to a decrease in the project cost, on the other hand, the additional direct costs required for acceleration will outweigh the amount of indirect cost savings due to the duration reduction.

Achieving a suitable trade-off between the cost and duration of a project is thus an intricate and computationally challenging problem solving which necessitates taking a systematic approach. The issue of balancing time and cost in a project, which is commonly known as the time-cost trade-off problem (TCTP), has been widely recognized in the literature and studied under various assumptions. Within the body of literature, there are three common types of the time-cost trade-off problem (TCTP) that have been studied: the deadline problem, the budget problem, and the Pareto front problem. The goal of the deadline problem is to identify a set of time-cost alternatives that will minimize the total cost of a project, including bonuses and penalties, while adhering to a given deadline [1,2]. The budget problem, on the other hand, seeks to minimize the duration of the project without exceeding the allotted budget [3]-[6]. Finally, the Pareto front problem, being the focus of this study, involves identifying the non-dominated time-cost profile over the set of feasible project durations to generate the efficient frontier known as the Pareto front [7].

The research area of TCTP first emerged in the 1960s, coinciding with the introduction of project network analysis techniques by Kelley and Walker [8], Fulkerson [9], and Kelley [10]. Since then, there has been significant progress in this domain, fueled by advancements in computer science and technology. There exists a substantial body of research that focuses on different variants of this problem and seeks to develop effective solutions that can help decision-makers navigate the complexities involved in balancing time and cost objectives. As such, it has attracted significant attention from scholars, researchers, and practitioners alike, who pursue developing practical solutions that can be applied in real-world situations. The ongoing efforts to develop more effective and efficient methods for managing the TCTP reflect the importance of this problem in project management and the significant impact it can have on a project's success. These methods mainly include heuristics, exact approaches, among others. Such methods differ in terms of their computational complexity, solution quality, and applicability to real-world situations. Due to their capability in locating the optima, many exact approaches have been used to model TCTP, such as linear programming proposed by Kelley [10], dynamic programming by Butcher [3], hybrid linear/integer programming by Liu et al. [11], and branch-and-bound algorithm by Demeulemeester et al. [2]. Though, it is a well-known fact that exact methods tend to require great computational effort. Accordingly, several researchers have attempted to simplify TCTPs through various reduction techniques. As such, the notion of reducing the size of TCTP through mode elimination is not a new concept and has been previously explored in the literature for both the deadline and the budget problems. The most noteworthy of the studies on problem size reduction are due to Akkan et al. [12], Hafizoglu and Azizoglu [13], who explored utility of mode elimination in the deadline TCTP, as well as Degirmenci and Azizoglu [14], who examined the use of a similar technique in the budget TCTP.

However, to the best of author’s knowledge, this study is the first to examine the potential benefits of integrating mode elimination into the truly multi-objective Pareto front TCT problem. The proposed methodology employs a dynamic problem size reduction mechanism, which leads to the concept of adaptive mode elimination, and provides a novel contribution to the literature on TCTP research. By leveraging this approach, this study aims to enhance the efficiency and effectiveness of the solution procedure for Pareto front TCTPs, which are inherently complex and require decision-makers to consider multiple objectives instantaneously. Therefore, this study presents an ε-constraint method that incorporates an adaptive mode elimination technique to assist in achieving the optimal balance between project duration and cost specifically for large Pareto front TCTPs. The proposed approach entails an iterative process of solving the deadline TCTP over the complete set of feasible project durations via adjusting the ε value. At each level of ε, the size of the search space gets reduced with the aid of the clever adaptive mode elimination by detecting and discarding the redundant execution mode(s). The redundant modes are detected as the ones which cannot contribute to capturing of the current ε. The mixed integer linear programming (MILP) method is utilized to formulate and develop the proposed optimization model. In order to explore effectiveness of the present method, a benchmark TCTP is borrowed from the literature. Comparisons are made between the reduced and unreduced search spaces highlighting the usefulness and efficacy of the proposed optimization model.

The remainder of this paper is organized as follows. Section 2 elaborates on the steps of the proposed optimization model. In Section 3, the proposed approach is experimented for reduction of multi-objective search space. Finally, Section 4 provides conclusions.

2. Methodology

As an activity gets expedited, a decline in productivity is expected to happen after a certain point due to several reasons including congestion of the construction site. Accordingly, individual activities forming a TCTP will lead to a convex solution space. Convexity of the solution space, on the other hand, facilitates converging to global optima even for large TCTPs using mathematical models, should there be no limitation on the processing computer's memory. In this study, the mathematical model is formulated using mixed integer linear programming (MILP) and Gurobi Solver version 9.5.1 is employed to solve the model. The proposed optimization procedure incorporates a particular strategy to reduce the problem size that helps solve complicated Pareto front problems with substantially reduced computational effort and time.

Mathematical formulation

The formulation used to construct MILP for Pareto front time-cost trade-off problem is given in Eqs. (1)-(7).

$$minimize \quad \mathbf{f} = (f^{(1)}, f^{(2)}) \tag{1}$$

$$f^{(2)} = \sum_{j=1}^{S} \sum_{k=1}^{m(j)} (dc_{jk} x_{jk}) + f^{(1)} \times ic \tag{2}$$

subject to:

$$\sum_{k=1}^{m(j)} x_{jk} = 1 \quad , \quad \forall j \in \{1, ..., S\} \tag{3}$$

$$\sum_{k=1}^{m(j)} d_{jk} x_{jk} + St_j \leq St_l \quad , \quad \forall l \in Sc_j \quad \text{and} \quad \forall j \in \{1, ..., S\} \tag{4}$$

$$f^{(1)} \leq \varepsilon \tag{5}$$

$$f^{(1)} \geq Ft_S \tag{6}$$

$$St_0 = 0 \tag{7}$$

where; $f^{(1)}$ denotes the first objective function, i.e., duration; $f^{(2)}$ denotes the second objective function, i.e., cost; dc_{jk} is the direct cost of k-th mode of j-th activity; x_{jk} is a binary variable which is set to 1 when k-th mode is selected for j-th activity, is set to 0 otherwise; ic denotes the rate of daily indirect cost; d_{jk} is the duration of k-th mode of j-th activity; St_j is the start time of j-th activity; Ft_j denotes the finish time of j-th activity; and Sc_j is the set of immediate successors for j-th activity. Eq. (1) defines the objective function for the Pareto front TCTP. Objective function of cost is calculated per Eq. (2). Constraint defined as Eq. (3) secures selection of only a single time-cost alternative at a time for each activity. The precedence relationships are sustained using Eq. (4). Constraints defined as Eqs. (5) and (6) represent the bounds on project duration based on ε's value and the finish time of the last activity. Start time of the first activity is set using Eq. (7).

Adaptive mode elimination technique

As discussed earlier, reducing the dimensionality of a problem would exponentially decrease the search space, leading to a significant reduction in computational effort. One way to decrease the dimension of a TCTP is to systematically eliminate the execution modes that cannot contribute to achievement of a particular project duration. This problem size reduction technique is hailed as mode elimination which is established based on the preprocessing techniques described by Akkan et al. [12]. Mode elimination has been the subject of research studies focusing on deadline TCTP [12,13] and budget TCTP [14] but has never been deployed for solution of Pareto front TCTP. To address this gap in the literature, a clever adaptive mode elimination strategy is proposed in this study which specifically aids unravelling Pareto front TCTPs. The optimization model of the present study incorporates the adaptive mode elimination into the well-established ε-constraint method [15]. The ε-constraint-based method involves iterative solution of the deadline TCTP by sweeping ε from minimum possible duration to maximum possible duration in steps of one. At each level of ε, the adaptive mode elimination reduces the problem size by discarding the redundant time-cost mode(s) as follows. Initially, for each activity, the associated all-crashed mode is selected and CPM calculations are carried out. Next, the so-called long modes are identified per Eqs. (8)-(10) and eliminated since they cannot contribute to capturing of the current ε. Discarding the so-called short modes at the current ε level ensues subsequent to elimination of the long modes as follows. For each activity, the corresponding all-normal mode is selected and CPM calculations are performed. Next, short modes are eliminated per Eqs. (11)-(13) since their contribution to achieving the current value of ε is null.

eliminating long modes:

$$\delta_C = \varepsilon - LF_S \tag{8}$$

$$LF_j = LF_j + \delta_C \tag{9}$$

$$Decision \begin{cases} \text{if } LF_j - ES_j + 2 \le d_{jk} & \text{remove modes 1 to } k \\ \text{otherwise,} & \text{dismiss} \end{cases} \tag{10}$$

eliminating short modes:

$$\delta_N = \varepsilon - LF_S \tag{11}$$

$$LF_j = LF_j - \delta_N \tag{12}$$

$$Decision \begin{cases} \text{if } LF_j - ES_j + 1 > d_{jk} & \text{remove modes } k+1 \text{ to } m(j) \\ \text{otherwise,} & \text{dismiss} \end{cases} \tag{13}$$

$$\forall\ j \in \{1,...,S\} \quad \text{and} \quad \forall\ k \in \{1,...,m(j)\} \tag{14}$$

where; δ_C denotes the difference between ε and late finish time of the last activity in all-crashed schedule; LF_j represents the late finish time of j-th activity; ES_j is the early start time of j-th activity; d_{jk} denotes duration of k-th mode of j-th activity; and δ_N denotes the difference between ε and late finish time of the last activity in all-normal schedule.

Upon completion of the first round of mode elimination, the schedules containing the all-crashed and the all-normal modes are updated based on the remaining shortest and longest modes. Further elimination of long and short modes is carried out in accordance with the conditions outlined in Eqs. (8)-(14). This process of adaptive mode elimination is repeated until no further long or short modes can be eliminated using the aforementioned rules. As per the proposed optimization method, the simplified problem is utilized to identify the optimal solution for the current ε level. Following this, the value of ε is incremented by one, and the size reduction rules mentioned earlier are applied once again to reduce the search space. This process of mode elimination and optimization is then repeated iteratively until all feasible completion durations have been explored. Pseudo-code given in Fig. 1 describes the main steps involved in implementation of the proposed algorithm. The overview of this methodology is presented as a flowchart in Fig. 2. Based on the MILP formulation described in Eqs. (1)-(7) and the adaptive mode elimination rules presented in Eqs. (8)-(14), a Gurobi Optimization model is created using C# on Visual Studio 2019.

Algorithm (f)

$PF \leftarrow \varnothing$
While ($\varepsilon \leq \varepsilon_{\max}$) {
  Apply Mode Elimination rules (8)-(14) for ε
  Solve MILP formulation (1)-(7) for ε
  $Sol \leftarrow (f^{(1)} , f^{(2)})$
  if ($Sol \neq \text{nil} \wedge (\nexists\, Sol' \in PF : f^{(2)}_{Sol'} < f^{(2)}_{Sol}$)) {
    $PF \leftarrow (PF \cup \{Sol\}) \setminus \{Sol' \in PF : Sol \succ Sol'\}$ }
  $\varepsilon \leftarrow \varepsilon + 1$ }
return (PF)

Fig. 1. Pseudo-code of the proposed optimization method.

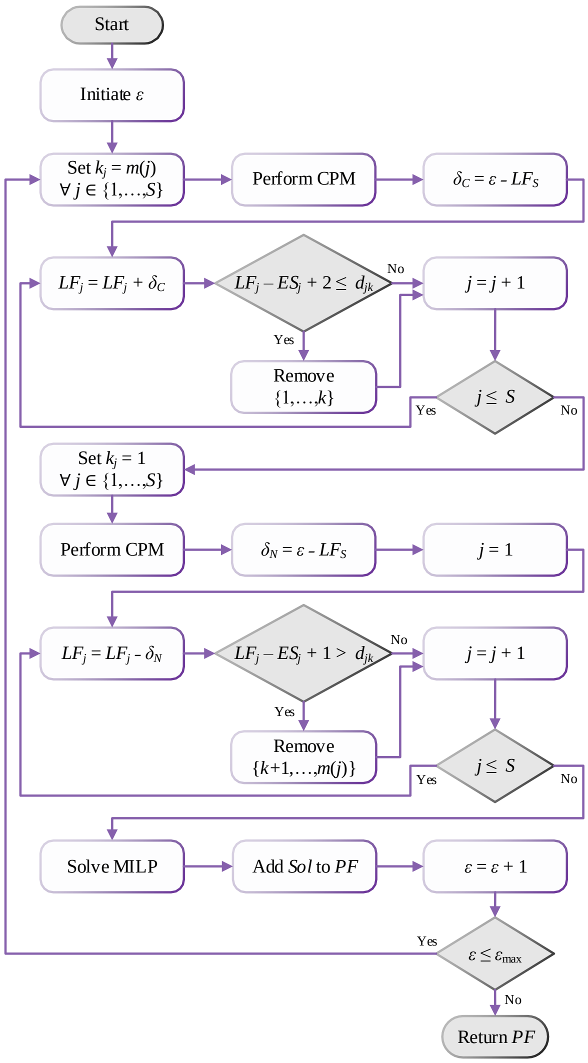

Fig. 2. Flowchart of the proposed optimization method.

3. Computational experiments

The proposed reduction strategy is experimented for optimization of a well-studied benchmark TCTP which was introduced by Hegazy [16]. The activity-on-node (AoN) representation as well as the time-cost modes of this problem are given in Fig. 3. As seen in Fig. 3, this TCTP contains 18 activities and up to five time-cost execution modes, with a single activity having two modes, ten activities with three modes, two activities with four modes, and five activities having five modes. Therefore, this problem can be configured in numerous distinct mode combinations, resulting in 5,904,900,000 possible schedules. The effects of the adaptive mode elimination strategy on the performance of the proposed optimization method is explored by comparing the results over this benchmark TCTP by assuming an indirect cost of $0/day.

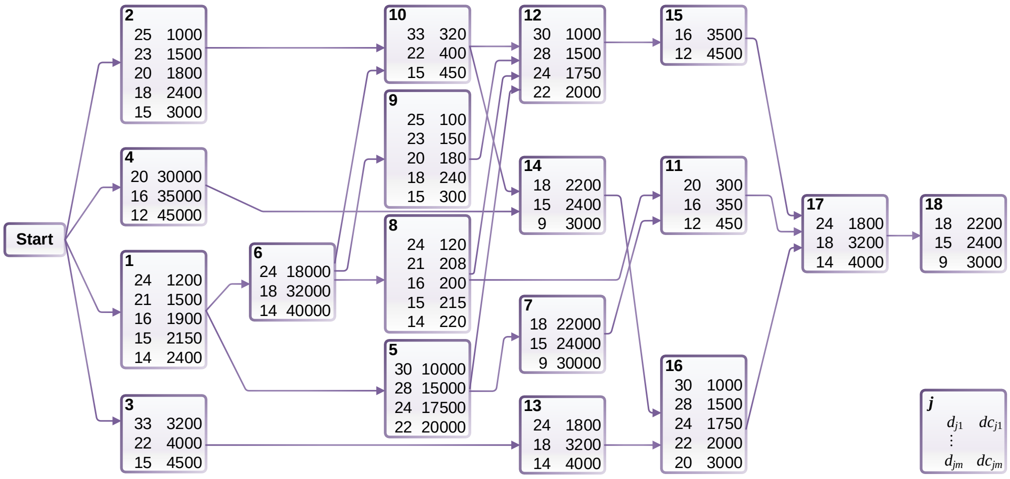

Fig. 3. Unreduced problem.

Table 1 provides the details of the obtained results by shedding light on the size of the reduced search spaces associated with every value of ε. In addition, a general overview of the impact of the mode elimination technique is covered in Table 2. As can be followed from Table 1, the ε-constraint-based method can achieve 44 non-dominated solutions ranging from (100 *day*, $133.320) to (169 *day*, $99,740). With reference to Table 2, size of the search space can be reduced at least by 96.29% down to size 218,700,000, for ε's 118, 119, 120, 121, 122, 124, and 125. On the other hand, the size of the search space is reduced by a maximum amount of 99.99% down to size 48, at ε=100. Figs. 4 and 5 are presented to exemplify how adaptive mode elimination removes the redundant modes at the two extreme points of ε=100 and ε=169, respectively. It should be pointed out that in these illustrations, the dimmed text indicates that the time-cost mode has been discarded. As can be followed from Fig. 4, there can be $1^{13}\times2^{4}\times3^{1}$, i.e., 48 possible configurations when all combinations of the retained modes are considered. Similarly, it can be seen from Fig. 5 that for the reduced problem, a total of $1^{11}\times2^{7}$, i.e., 128 different realizations are possible at ε=169. Such remarkable drops in the search space complexity can potentially lead to significant reductions in computational burden of Pareto-oriented TCTP analysis.

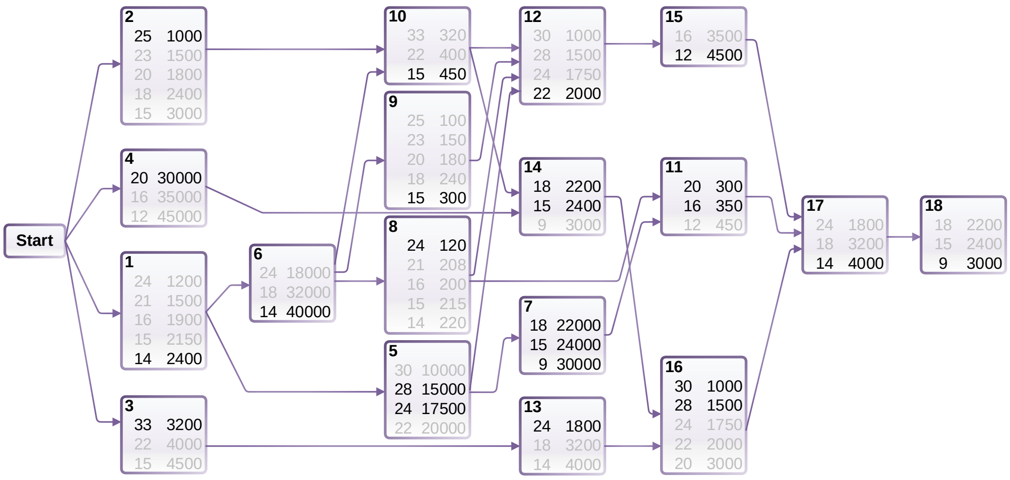

Fig. 4. Reduced problem at ε=100.

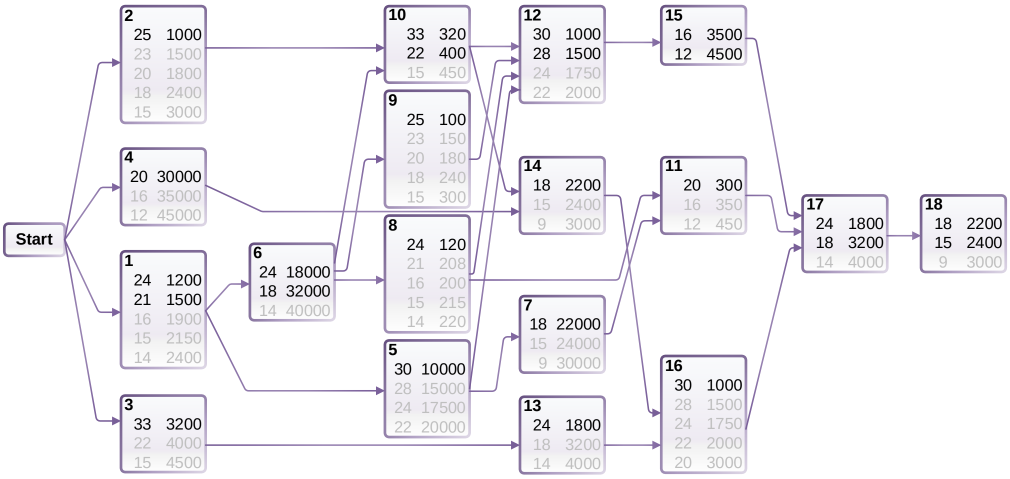

Fig. 5. Reduced problem at ε=169.

The potential of the adaptive mode elimination is demonstrated by successfully reducing the search space of the employed problem and the results are summarized in Table 1. The first row of this table (shown in italics) presents the unreduced number of available activity modes and the corresponding size of search space for any duration between 100 and 169 days. The remainder of the table provides insight as to how the mode elimination mechanism enables reducing the search space per each level of ε. The computational experiment indicate that the proposed method is capable of locating Pareto front for this instance by searching merely a significantly small fraction of the search space. In fact, as summarized in Table 2, only 3,013,047,572 possible schedules are explored instead of 259,815,600,000, subsequent to reducing the problem per the proposed strategy. This is due to the fact that a conventional ε-constraint method would have explored 44×5,904,900,000=259,815,600,000 number of schedules for this problem had it not been reduced by the adaptive mode elimination strategy. It can therefore be claimed that the proposed method is capable of capturing the entire efficient frontier by searching only 1.16% of the unreduced search space required to be explored for the 44 Pareto solutions.

Table 1. Pareto front achieved through iterative problem size reduction.

Duration (day)	Total Cost ($)	No. of Available Modes																		Search Space	Reduction (%)
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18		
100-169	*133,320-99,740*	*5*	*5*	*3*	*3*	*4*	*3*	*3*	*5*	*5*	*3*	*3*	*4*	*3*	*3*	*2*	*5*	*3*	*3*	*5,904,900,000*	*0.00*
100	133,320	1	1	1	1	2	1	3	1	1	1	2	1	1	2	1	2	1	1	48	99.99
101	128,320	2	1	1	1	3	1	3	1	1	1	3	1	1	2	1	2	1	1	216	99.99
102	128,070	3	1	1	1	3	1	3	1	1	1	3	2	1	2	1	2	1	1	648	99.99
103	127,820	3	1	1	1	3	1	3	1	2	1	3	2	1	1	1	1	1	1	324	99.99
104	120,320	3	3	1	1	4	2	3	2	2	1	3	2	1	2	2	3	2	1	124,416	99.99
105	120,070	3	3	1	1	4	2	3	2	3	1	3	2	1	2	2	2	2	1	124,416	99.99
106	119,820	3	5	1	1	4	2	3	3	3	1	3	3	1	3	2	4	2	2	2,799,360	99.95
107	119,770	4	5	1	1	4	2	3	5	3	2	3	3	1	3	2	5	2	2	15,552,000	99.73
108	119,270	4	5	1	1	4	2	3	4	4	2	3	4	1	3	2	5	2	2	22,118,400	99.62
109	119,020	4	5	1	1	4	2	3	5	4	2	3	4	1	3	2	5	2	3	41,472,000	99.29
110	106,270	5	5	1	1	4	3	3	5	5	2	3	4	1	3	2	5	3	3	145,800,000	97.53
111	106,020	5	5	1	1	4	3	3	5	5	2	3	4	1	3	2	5	3	3	145,800,000	97.53
112	105,770	5	5	1	1	4	3	3	5	5	2	3	4	1	3	2	5	3	3	145,800,000	97.53
114	105,270	5	5	1	1	4	3	3	5	5	2	3	4	1	3	2	5	3	3	145,800,000	97.53
115	105,020	5	5	1	1	4	3	3	5	5	2	3	4	1	3	2	5	3	3	145,800,000	97.53
116	104,770	5	5	1	1	4	3	3	5	5	2	3	4	1	3	2	5	3	3	145,800,000	97.53
118	104,470	5	5	1	1	4	3	3	5	5	3	3	4	1	3	2	5	3	3	218,700,000	96.29
119	104,220	5	5	1	1	4	3	3	5	5	3	3	4	1	3	2	5	3	3	218,700,000	96.29
120	103,970	5	5	1	1	4	3	3	5	5	3	3	4	1	3	2	5	3	3	218,700,000	96.29

Duration (day)	Total Cost ($)	No. of Available Modes																		Search Space	Reduction (%)
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**		
121	103,820	5	5	1	1	4	3	3	5	5	3	3	4	1	3	2	5	3	3	218,700,000	96.29
122	103,570	5	5	1	1	4	3	3	5	5	3	3	4	1	3	2	5	3	3	218,700,000	96.29
124	103,070	5	5	1	1	4	3	3	5	5	3	3	4	1	3	2	5	3	3	218,700,000	96.29
125	102,820	5	5	1	1	4	3	3	5	5	3	3	4	1	3	2	5	3	3	218,700,000	96.29
126	102,570	5	5	1	1	4	3	3	4	5	3	3	4	1	3	2	5	3	3	174,960,000	97.03
128	102,320	5	5	1	1	4	3	3	3	5	3	3	4	1	3	2	5	3	3	131,220,000	97.77
131	102,170	5	5	1	1	4	3	3	3	5	3	2	4	1	3	2	5	3	3	87,480,000	98.51
132	101,970	5	5	1	1	4	3	2	2	5	3	2	4	1	3	2	5	3	3	38,880,000	99.34
133	101,820	5	5	1	1	4	3	2	2	5	3	2	4	1	3	2	5	3	3	38,880,000	99.34
134	101,570	5	5	1	1	4	3	2	2	5	3	2	4	1	3	2	5	3	3	38,880,000	99.34
137	101,510	5	5	1	1	3	3	1	1	5	3	1	4	1	3	2	5	3	3	3,645,000	99.93
138	101,470	5	5	1	1	3	3	1	1	5	3	1	4	1	3	2	5	3	3	3,645,000	99.93
139	101,170	5	5	1	1	3	3	1	1	5	3	1	4	1	3	2	5	3	3	3,645,000	99.93
140	100,970	5	4	1	1	3	3	1	1	5	3	1	4	1	3	2	4	3	3	2,332,800	99.96
142	100,870	5	3	1	1	2	3	1	1	5	3	1	4	1	3	2	3	3	3	874,800	99.98
143	100,770	5	3	1	1	1	3	1	1	5	3	1	4	1	3	2	3	3	3	437,400	99.99
145	100,570	5	2	1	1	1	3	1	1	5	3	1	4	1	2	2	3	3	3	194,400	99.99
148	100,270	5	1	1	1	1	3	1	1	5	3	1	4	1	1	2	1	3	3	16,200	99.99
151	100,070	5	1	1	1	1	3	1	1	5	3	1	4	1	1	2	1	3	3	16,200	99.99
154	100,010	5	1	1	1	1	3	1	1	5	3	1	4	1	1	2	1	3	3	16,200	99.99
156	99,950	5	1	1	1	1	3	1	1	4	3	1	4	1	1	2	1	3	3	12,960	99.99
158	99,900	5	1	1	1	1	3	1	1	3	3	1	4	1	1	2	1	3	3	9,720	99.99
159	99,870	5	1	1	1	1	3	1	1	3	2	1	4	1	1	2	1	3	3	6,480	99.99
161	99,820	4	1	1	1	1	3	1	1	2	2	1	4	1	1	2	1	3	3	3,456	99.99
169	99,740	2	1	1	1	1	2	1	1	1	2	1	2	1	1	2	1	2	2	128	99.99

Table 2. Search space comparison for unreduced and reduced problems.

Description	Value
Size of smallest reduced search space	48
Size of largest reduced search space	218,700,000
Size of avg. reduced search space	68,478,354
Min reduction in search space (%)	96.29
Max reduction in search space (%)	99.99
Overall size of unreduced search space for locating 44 Pareto solutions	259,815,600,000
Overall size of reduced search space for locating 44 Pareto solutions	3,013,047,572
Percent reduction in overall size of search space for locating 44 Pareto Sols (%)	98.84

4. Conclusions

The significance of achieving an adequate balance between cost and duration of a project has been already well debated in the time-cost trade-off problem (TCTP) literature. However, studies focusing on this matter have scarcely addressed the potential of reduction techniques for Pareto front TCTPs. Of the problem size reduction technique, mode elimination has been the subject of research studies focusing on deadline and budget TCTPs but has never been deployed for solution of the more complex Pareto front variant. Accordingly, this study proposes a clever adaptive mode elimination strategy particularly designed for unravelling Pareto front TCTPs. The optimization model of the present study is based on the conventional ε-constraint method featuring the proposed clever adaptive mode elimination strategy. This optimization model is formulated and developed using mixed integer linear programming (MILP) and its effectiveness is experimented using a benchmark TCTP taken from the literature. It is shown that by leveraging this approach, the entire efficient frontier of the benchmark instance can be captured by exploring less than two percent of the overall unreduced search space. Such remarkable reductions in the solution space can potentially speed up the search and lower computational complexity of Pareto front TCTPs that are inherently complicated and require decision-makers to consider multiple objectives instantaneously.

References

[1] E. Demeulemeester, W. Herroelen, and S. E. Elmaghraby, “Optimal procedures for the discrete time/cost trade-off problem in project networks,” European Journal of Operational Research, vol. 88, no. 1, pp. 50–68, Jan. 1996, doi: 10.1016/0377-2217(94)00181-2.
[2] E. Demeulemeester, B. De Reyck, B. Foubert, W. Herroelen, and M. Vanhoucke, “New computational results on the discrete time/cost trade-off problem in project networks,” Journal of the Operational Research Society, vol. 49, no. 11, pp. 1153–1163, Nov. 1998, doi: 10.1057/palgrave.jors.2600634.
[3] W. S. Butcher, “Dynamic Programming for Project Cost-Time Curves,” Journal of the Construction Division, vol. 93, no. 1, pp. 59–74, Mar. 1967, doi: 10.1061/jcceaz.0000191.
[4] D. Robinson, “A Dynamic Programming Solution to Cost-Time Tradeoff for CPM,” Management Science, vol. 22, no. 2, pp. 158–166, Oct. 1975, doi: 10.1287/mnsc.22.2.158.
[5] S. E. Elmaghraby, “Resource allocation via dynamic programming in activity networks,” European Journal of Operational Research, vol. 64, no. 2, pp. 199–215, Jan. 1993, doi: 10.1016/0377-2217(93)90177-o.
[6] Ö. Hazır, M. Haouari, and E. Erel, “Discrete time/cost trade-off problem: A decomposition-based solution algorithm for the budget version,” Computers & Operations Research, vol. 37, no. 4, pp. 649–655, Apr. 2010, doi: 10.1016/j.cor.2009.06.009.
[7] M. Vanhoucke and D. Debels, “The discrete time/cost trade-off problem: extensions and heuristic procedures,” Journal of Scheduling, vol. 10, no. 4–5, pp. 311–326, Oct. 2007, doi: 10.1007/s10951-007-0031-y.
[8] J. A. Kelley and M. M. Walker, “Critical-path planning and scheduling,” Papers Presented at the December 1-3, 1959, Eastern Joint IRE-AIEE-ACM Computer Conference On - IRE-AIEE-ACM ’59 (Eastern), Dec. 1959, doi: 10.1145/1460299.1460318.
[9] D. R. Fulkerson, “A Network Flow Computation for Project Cost Curves,” Management Science, vol. 7, no. 2, pp. 167–178, Jan. 1961, doi: 10.1287/mnsc.7.2.167.
[10] J. A. Kelley, “Critical-Path Planning and Scheduling: Mathematical Basis,” Operations Research, vol. 9, no. 3, pp. 296–320, Jun. 1961, doi: 10.1287/opre.9.3.296.
[11] L. Liu, S. A. Burns, and C. W. Feng, “Construction Time-Cost Trade-Off Analysis Using LP/IP Hybrid Method,” Journal of the Construction Division and Management, vol. 121, no. 4, pp. 446–454, Dec. 1995, doi: 10.1061/(asce)0733-9364(1995)121:4(446.
[12] C. Akkan, A. Drexl, and A. Kimms, “Network decomposition-based benchmark results for the discrete time–cost tradeoff problem,” European Journal of Operational Research, vol. 165, no. 2, pp. 339–358, Sep. 2005, doi: 10.1016/j.ejor.2004.04.006.
[13] A. B. Hafizoglu and M. Azizoglu, “Linear programming based approaches for the discrete time/cost trade-off problem in project networks,” Journal of the Operational Research Society, vol. 61, no. 4, pp. 676–685, Apr. 2010, doi: 10.1057/jors.2009.20.
[14] G. Degirmenci and M. Azizoglu, “Branch and bound based solution algorithms for the budget constrained discrete time/cost trade-off problem,” Journal of the Operational Research Society, vol. 64, no. 10, pp. 1474–1484, Oct. 2013, doi: 10.1057/jors.2012.14.
[15] Yv. Haimes Yv., L. Lasdon, and D. Da, “On a Bicriterion Formulation of the Problems of Integrated System Identification and System Optimization,” IEEE Transactions on Systems, Man, and Cybernetics, vol. SMC-1, no. 3, pp. 296–297, Jan. 1971, doi: 10.1109/tsmc.1971.4308298.
[16] T. Hegazy, “Optimization of construction time-cost trade-off analysis using genetic algorithms,” Canadian Journal of Civil Engineering, vol. 26, no. 6, pp. 685–697, Dec. 1999, doi: 10.1139/l99-031.

ANALYSIS OF POTENTIAL SCHEDULE-DELAYING ELEMENTS FOR VOLUMETRIC MODULE TRANSPORTATION

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Abstract

Modular construction is well known for its ability to provide numerous productivity and overall cost benefits over the conventional stick-built method through sophisticated off-site environments. However, although the advantages of modular construction are recognized, it is still considered a secondary means for delivering construction projects in the U.S. Consequently, modular projects often fail to achieve full benefits due to stakeholders' lack of expertise and experience. Existing studies examined the on- and off-site modular process optimization, whereas module transportation is relatively unconsidered. Among the modular benefits, the expedition of construction project schedules is paramount as it directly impacts the project delivery time. A meaningful portion of time for modular projects is allocated for transporting the completed module to its final installation spot, and its optimization will contribute to the project schedule expedition. Accordingly, this paper, through the examination of the volumetric modular house transportation project, will identify potential schedule-delaying elements and recommend corrective measures that will minimize, if not eliminate them. Transportation time stamps were collected with the two sets of 2 channel dashcams installed inside the module and divided into three stages (Lifting, Transporting, and Offloading). The modular project took two days to complete, going over the anticipated 10-hour duration. The most impactful schedule-delaying elements originated from the use of lumber stacks as temporary supports for hydraulic jacks and disconnected tandem axle dollies for the bogey support system. The analysis conducted by this paper will help industry stakeholders eliminate the schedule-delaying elements of modular transportation projects and achieve the full benefits of modular construction.

Keywords: construction optimization, modular challenges, modular construction, modular drivers, module transportation.

Introduction

In essence, modular construction substitutes most of the on-site work hours, with off-site work hours, and in controlled off-site factory environments [1]. Off-site module manufacturing tasks and remaining on-site tasks, such as foundation work, can be commenced concurrently, which is one of the biggest advantages of modular construction over stick-built methods [2,3]. However, as it stands, the stick-built method is still adopted in the U.S. construction industry as the primary method for delivering construction projects [1].

There exist distinct differences and constraints, with the most notable ones including module design envelope considerations, high initial investment costs, and enhanced coordination and alignment on goals among project stakeholders from the early project planning phase [4].

These constraints must be met in order to successfully obtain the full benefits of using modular construction – which the stick-built accustomed U.S. construction stakeholders struggle to address, hindering a smooth transition from one method to another [5]. Such transition-hindering elements are often labeled as ‘modular challenges’ and pose the need for research efforts to establish appropriate measures to help the companies incur full modular benefits. Many research efforts have been allocated to bridge the expertise and experience gap through the identification of critical factors dictating modular projects’ performances to aid stakeholders in adopting appropriate practices and making modular decisions [6,7,8,9].

The modular construction processes include an additional phase of transporting the off-site manufactured module to its final job site location via tractor-trailers on the roads. A meaningful portion of time is allocated for this additional phase. First, the module is lifted at the fabrication location, most commonly using cranes or forklifts [10]. Second, the module is loaded and secured to the trailer beds. Last, the module is unloaded at its on-site installation spot, marking the completion of the transportation phase. In the U.S., the current module transporting practices are often unoptimized, meaning modular projects experience schedule losses during the transportation phase.

Despite the aforementioned shortcomings, no previous research was identified that examined the potential module transportation schedule optimization. Therefore, this paper conducted a case study with the transportation of a volumetric modular house, ‘Mojave Bloom,’ fabricated by the team Las Vegas from the University of Las Vegas, Nevada, for the 2021 Solar Decathlon competition to identify potential schedule-delaying elements. Time stamps for each notable activity were created, and their schedule efficiency was validated by rationalizing the total time consumed to complete them. Ultimately, this paper recommends more schedule-efficient alternative practices and/or equipment to lift, transport, and offload the volumetric module.

Literature Review

For lifting and offloading multi-module structures, it is optimal to use the crane [11]. Limited Jobsite access, overhead power lines, and public safety concerns are the notable constraints of using crane lifting. Thus, forklifts or other more flexible substitute means of lifting equipment could be more desirable. The modular construction industry does not have federally regulated building codes such as HUD-Code [12]. Therefore, the volumetric module's dimensions and weight can vary, and they are mainly dictated by the respective states' building codes from which the modules are being manufactured and delivered. The volumetric modules typically weigh up to tens of thousands of pounds and have widths ranging from 10 ~ 16 ft., with 12 and 14 ft. being the most common. The length spans up to 70 ft. with 2 ft. increments and the height ranges from 11 ft. to 13 ft [5,12]. The cost increases as the transportation distance increase, thus the typical maximum transportation distance is 125 miles, and anything beyond that is considered economically impractical [13,14].

The review conducted considered the volumetric module transportation to comprise three sub-phases: Lifting (1), Transporting (2), and Offloading (3), and it was identified that design compliance and safety were the most common research themes among the previous studies. No study was identified that examines the potential modular project schedule expedition by optimizing the three transportation sub-phases. A decent portion of the modular project schedule is dedicated to the transportation phase – its optimization will meaningfully compress the overall project schedule, and the lack of research led to the recognition of the need for research.

This paper aims to identify schedule-delaying unoptimized lifting, transporting, and offloading practices for a Mojave Bloom modular house transportation project based on the time stamps created using dashcam footage and ShockLog time data slots for each activity, and, upon the completion of identification, corrective measures will be rationalized.

Methodology

The selected modular house subjected for the transportation and case study was 'Mojave Bloom,' designed and developed by UNLV's 2021 Solar Decathlon team and Design+Build Studio. The modular house was first located at the off-site fabrication yard on top of the steel piers. A hydraulic jack supported by a lumber stack was used for the lifting and was installed at each corner of the modular house. For transportation, two tandem axle dollies were attached underneath the rear of the modular house, and its front was attached to the fifth wheel hitch of a truck tractor. Hydraulic jacks and lumber stacks were used again to offload the modular house. The measures adopted for the lifting, transportation, and offloading phases are visually represented in Figure 1.

Figure 1. Lifting with hydraulic jacks (left), Transportation using tandem axle dollies (middle), Offloading with hydraulic jacks (right)

The sub-phase 'transportation' in this paper indicates the period between when the modular house exited the fabrication yard and when it arrived at its installation spot. The transportation distance was approximately 13.2 miles from the off-site location to the final job-site location. The work stopped with the completion of the Transportation phase and resumed the following day with the offloading phase.

ShockLog 298 sensor and two sets of BlackVue DR750-2CH dash cameras were installed inside the modular house for data collection. The sensor was set to record time slots once every ten seconds through all processes of the transportation. The dash camera footage displayed the time and speeds at which the modular house was traveling. The recorded time slots were exported in CSV format. The time slots collected before the commencement of the lifting phase and after the completion of the offloading phase were discarded. After the screening process, time slots were manually matched accordingly with the speeds displayed on the dash cameras for the transportation sub-phase. The matched data points were then distributed into the three sub-phases by visually referencing the footage recorded for making distinctions among the sub-phases. The analysis was conducted for each sub-phase based on the allotted data and recommendations on alternative corrective measures are discussed in the discussion section. The overall workflow adopted for this paper is illustrated in Figure 2.

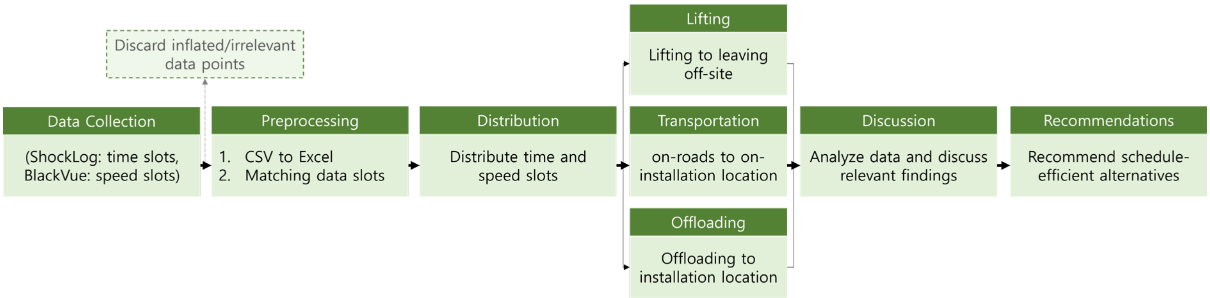

Figure 2. Module transportation schedule-delaying elements analysis workflow

Results and Discussion

The Mojave Bloom modular house transportation project took two days to complete, going over the anticipated 10-hour duration. Excluding the idle time when the transportation was halted, the project took 15 hours and 30 minutes to complete. The time stamps for each phase and their respective descriptions are shown in Table 1.

Table 1. Transportation time stamps

Phases	Time Stamps	Description
Lifting	8:34 AM	Begin lifting
	12:56 PM	Attached to truck
	2:09 PM	Leaving Off-site
Transportation	2:10 PM	On road
	2:18 PM	Bogey support failure
	2:28 PM	Resumed
	3:18 PM	Job-site arrival
	5:32 PM	Installation spot
Offloading	8:50 AM	Begin offloading
	12:13 PM	Equipment removed
	3:20 PM	Approximate completion

Lifting

A few layers of lumber stacks were utilized with each hydraulic lift as its lifting capacity could not lift the modular house high enough to install the two axle dollies, and a wooden beam was used to establish a bogey support system by connecting the two axle dollies. The front side of the modular house was lifted once again after installing the axle dollies to be connected to the truck's fifth wheel. Table 1 shows that there was a delay of 1 hour 14 minutes after the modular house was lifted, which was necessary to balance the bogey support system and the truck tractor with the modular house. In total, the lifting phase took 5 hours and 35 minutes to complete.

Transportation

The transportation took 3 hours and 22 minutes to complete. While on the roads, a wooden beam used as a part of the bogey support system failed and caused a delay of 10 minutes. Due to the balancing issues, the modular house was traveling noticeably slower than the posted speed limits, taking a total of 58 minutes of on-road time for 13.2 miles distance – a 32-minute trip assuming moderate congestion according to Google Maps. The traveling speeds of the modular house on roads are represented in Figure 3.

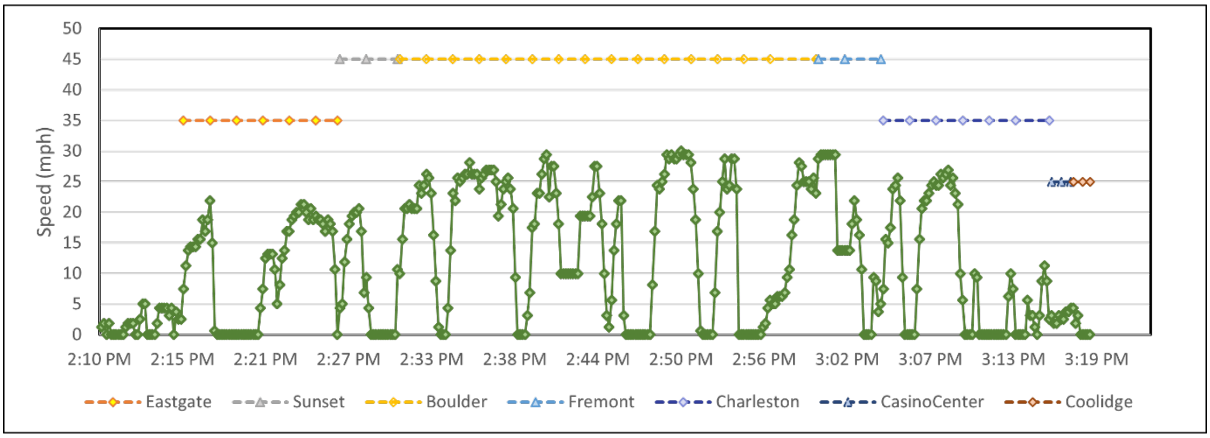

Figure 3. Traveling speeds vs. posted speed limits

The transportation route included seven different roads and excluded highways. There were thirteen stops, and excluding these instances, the average traveling speed of the modular house was 14 mph, and the top speed was only 30 mph in the 45-mph zone. The posted speed limits were 25, 35, and 45 mph. On average, the traveling speed was 59% slower than the posted speed limit. The entrance to the job site was extremely limited, with a 6-inch concrete slab on its path, as shown in Figure 4. Given the balancing issues with the bogey support system, a careful and time-consuming maneuver was necessary. The modular house was located at its installation spot 2 hours and 14 minutes after it arrived at the job site.

Figure 4. Modular house job site installation spot

Offloading

The work halted for the day and resumed after 15 hours and 18 minutes of idle phase with offloading phase, which took approximately 6 hours and 33 minutes to complete. As shown in Figures 1 (right) and 4, two sections of the metal fences lined up adjacent to the modular house were temporarily removed to allow sufficient space for hydraulic lift and lumber stacks to be placed. The hydraulic lifts then directly offloaded the modular house, marking the completion of the Mojave Bloom transportation project.

Conclusion and Recommendation

This paper conducted case study research with the Mojave Bloom transportation project to identify the potential schedule-delaying elements in the practices adopted. Given the originally anticipated 10-hour duration and counting the 15 hours and 18 minutes long idle phase, the accumulated delays throughout all phases of the modular house transportation was 15 hours and 48 minutes. Among all elements identified, the use of the alternatives for lifting and transporting measures in hydraulic jacks + lumber stacks and a bogey support system comprising two disconnected tandem axle dollies + a wooden beam were the two most impactful schedule-delaying elements. During lifting, the need for manual stacking of lumbers incurred schedule delays. A wooden beam failure that occurred after eight minutes of being on the road only resulted in 10 minutes of delay, but it could have caused a more significant delay. On roads, the modular house was traveling on average 59% slower than the posted speed limits due to the balancing issues with the bogey support system, which led to a delay of 26 minutes. Similar to lifting and transportation, the lumber stacks and bogey support system have caused delays during the offloading phase.

As discussed earlier in the literature review section, Forklifts had been a well-known flexible alternative to crane lifting, but a case with the Mojave Bloom validates the use of hydraulic jacks as another alternative method for lifting. However, it seems desirable to adopt hydraulic jacks with sufficient lifting capacity to avoid having to additionally lift the modular house manually. The bogey support system as an alternative for the typical flatbed tractor-trailer was also validated to an extent, but the use of axle dollies with pre-established connections is recommended.

The typical maximum transportation distance of a volumetric module is 125 miles, and the Mojave Bloom was only transported for 13.2 miles. If the distance was to be longer, the schedule delays incurred from avoiding highways and traveling on average 59% slower than the speed limits could have been more impactful. Moreover, no other case projects that provided the time consumed to complete each of the lifting, transporting, and offloading phases of the volumetric module using other alternative equipment were available. A comparison of times spent for each phase of each project was unavailable, hindering full validation of the schedule delays identified in this paper. Regardless, this paper identified potential schedule-delaying elements and recommended adequate corrective measures that will help the practitioners optimize module transporting practices to incur the full benefits of modular construction.

Acknowledgments

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References

[1] J. O. Choi, J. T. O'Connor, Y. H. Kwak, and B. K. Shrestha, "Modularization Business Case Analysis Model for Industrial Projects," Journal of Management in Engineering, vol. 35, no. 3, May 2019, doi: 10.1061/(asce)me.1943-5479.0000683.

[2] R. E. Smith, "Off-Site And Modular Construction Explained," National Institute of Building Sciences, 2016

[3] S. Nam, J. Yoon, K. Kim, and B. Choi, "Optimization of Prefabricated Components in Housing Modular Construction," Sustainability, vol. 12, no. 24, p. 10269, Dec. 2020, doi: 10.3390/su122410269.

[4] J. T. O'Connor, W. J. O'Brien, and J. O. Choi, "Critical Success Factors and Enablers for Optimum and Maximum Industrial Modularization," Journal of Construction Engineering and Management, vol. 140, no. 6, Jun. 2014, doi: 10.1061/(asce)co.1943-7862.0000842.

[5] R. Azari, N. Javanifard, D. Markert, K. Strobel, and J. Yap, "Modular Prefabricated Residential Construction: Constraints and Opportunities," University of Washington, PNCCRE Tech. Rep. TR-002, Aug. 2013.

[6] I. Y. Wuni, G. Q. P. Shen, and A. T. Mahmud, "Critical risk factors in the application of modular integrated construction: a systematic review," International Journal of Construction Management, vol. 22, no. 2, pp. 133–147, May 2019, doi: 10.1080/15623599.2019.1613212.

[7] Y. Sun et al., "Constraints Hindering the Development of High-Rise Modular Buildings,"

Applied Sciences, vol. 10, no. 20, p. 7159, Oct. 2020, doi: 10.3390/app10207159.

[8] B.-G. Hwang, M. Shan, and K.-Y. Looi, “Key constraints and mitigation strategies for prefabricated prefinished volumetric construction,” Journal of Cleaner Production, vol. 183, pp. 183–193, May 2018, doi: 10.1016/j.jclepro.2018.02.136.

[9] J. O. Choi, X. B. Chen, and T. W. Kim, “Opportunities and challenges of modular methods in dense urban environment,” International Journal of Construction Management, vol. 19, no. 2, pp. 93–105, Oct. 2017, doi: 10.1080/15623599.2017.1382093.

[10] M. Lawson, R. Ogden, and C. Goodier, “Design in Modular Construction,” Feb. 2014, doi: 10.1201/b16607.

[11] P. J. Cameron and N. G. di Carlo, “Piecing together modular : understanding the benefits and limitations of modular construction methods for multifamily development,” PhD dissertation, Massachusetts Institute of Technology, 2007.

[12] Modular Building Institute (MBI), “Permanent Modular Construction Report 2019,” Charlottesville, VA, USA: Modular Building Institute, 2019.

[13] T. Salama, A. Salah, O. Moselhi, and M. Al-Hussein, “Near optimum selection of module configuration for efficient modular construction,” Automation in Construction, vol. 83, pp. 316–329, Nov. 2017, doi: 10.1016/j.autcon.2017.03.008.

[14] R.E. Smith, “Transportation,” in *Prefab Architecture: A Guide to Modular Design and Construction,* J. Timberlake, Ed., Hoboken, NJ, USA: Wiley, 2010, pp. 193-205.

AUTOMATE AND STANDARDIZE MULTI-STORY BUILDING SCHEDULES THROUGH REPETITIVE SPATIOTEMPORAL MODEL

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Abstract
Traditional planning models, based on Gantt-Precedence logic, focus on defining activities and establishing their constraints. Resources can then be assigned to those activities. Spatial constraints are usually neglected, resulting in site congestion or relaxation. This is due to the lack of representation of the sequence of work and supply flows on the site. Spatiotemporal models are considered more appropriate, especially for planning the construction of buildings projects. These models simultaneously consider activities, resources, and space as constraints to construct a realistic execution schedule. In addition, multi-story buildings share many common components and activities. Thus, it is plausible to think of establishing standardization in order to create an automated system to support the construction of validated schedules. The objective of this study is to develop an automated and standardized approach for creating construction schedules for multi-story buildings. Using the data from many studies, a mapping of multi-story construction schedules through repetitive spatiotemporal approaches can be created to allow for a consistent and systematic representation of the schedule.

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Keywords: Schedule, Automate, Multi-story buildings, Repetitive, Spatiotemporal.

1. Introduction

For planning building construction projects, the Gantt/Precedence diagram, which presents the critical path of execution, has an almost absolute monopoly. Despite this, managers still encounter many difficulties in using this method, despite countless research works aimed at improving it. In addition to the anomalies related to the calculation of the critical path and the activities margins, this method is unsuitable for the planning of repetitive building projects, because it is difficult to show the sequence of work in the different units, zones or floors. Spatiotemporal scheduling is then more appropriate due to its ability to consider activities, resources and spaces simultaneously. The strength of this modelling lies in its ability to easily simulate different site conditions in graphical form and acting as a visual optimization tool that does not require complex calculations based on incomplete parameters, as suggested by algorithmic optimization methods. The objective of this study is to develop an automated and standardized approach for creating construction schedules for multi-story buildings. Using the data from many studies, a mapping of multi-story construction schedules through repetitive spatiotemporal approaches can be created to allow for a consistent and systematic representation of the schedule.

The main objective of this research is to automate and standardize multi-story building construction schedules using repetitive spatiotemporal models. The goal is to use spatiotemporal models that link spatial and temporal aspects, promote efficient site utilization, and ensure suitable rotation of the workforce as the basis for normalizing multi-story construction schedules.

2. Linear Projects

Planers and the researchers share their disagreement to apply the Bar chart and the Critical path Method CPM to the linear projects. The essential reason is the weaknesses of these methods to apply changes to the various repetitive units. [1] note that the CPM are unable to distinguish between the progression rate of activities and the number of completed units. Another reason is that they do not support a continuity of use of each type of resource. The concept of these methods rests on the fact that the interventions of the resources are specific and planning is directed according to requirements of precedence between the activities. [2] mentions that schedules oriented by resources are more realistic than those dominated by activities. These methods show graphically any imbalance due to uneven progress of activities and quickly allow the manager to quantify the deviation [3]. The inability of CPM to accurately model the continual and repetitive nature of linear construction has been identified by several authors [4; 5; 1]. Briefly, these limitations include arbitrary division of repetitive activities from one location to another, inability to plan continuity of resources, large number of activities required to represent a repetitive or linear project, difficult to visualize the rate of progress of activities. CPM does not accurately reflect the status and progress of activities at the project site [6]. The work of [7, 8] to determine the critical activities in linear planning was an important step in getting industry agreement to incorporate it. Linear methods were designed to plan projects such as roads and railways. In these projects, the machinery performs the work in a continuous and linear manner.

2.1. The beginning of linear methods - a short history

The Line of Balance method was developed to respond to linear projects and promote continuity of use of the workforce. This method is designed to maintain the sequence of each specialty between the different units. An approach that prioritizes the critical space on the critical path of activities is proposed. Several alternatives of this method have brought improvements such as varying progress rates, representing work interruptions.

2.2. The combination of LOB and CPM

Several works have been developed to combine the advantages of CPM and LOB. In the beginning, [9] integrated the planning tools of the PERT method with the control elements of the LOB. [10] proposed a technique for compressing networks. This technique uses a CPM to analyse the project. This is translated to a diagram. Then, using linear programming, the network is compressed and the resulting extra cost is calculated.

[11] developed an approach called Repetitive Project Model (RPM). This approach incorporates three techniques: a network technique, a graphical technique and an analytical technique. The network technique uses the presentation of ADM to define the activities and their dependencies for a typical repeating unit. The graphical technique establishes the time/cost curve of each activity and the flow curve. The latter represents the movement of a work team for an activity from the initial state until the end of the project. The slope of each line shows the production rate for each activity. The analytical technique uses linear programming for its mathematical formulation.

In 1991, [12] developed a mathematical method that calculates the duration of the project, the beginning and the end of each activity for each repeating unit. [1] developed a method that combines CPM and LOB. The method uses CPM for non-repetitive activities to avoid burdening the network and LOB for repetitive activities. [13] have developed a method that considers the work surfaces required for the storage of equipment and for the movement of labour on the site. This method reduces the conflicts that may exist on construction sites and improves team productivity. [14] used a method that combines CPM and LOB. Through the CPMs, they produce a typical unit. For this unit, the critical path is calculated and the parallel branches are defined. [15] propose PICASSO a hybrid diagram which combines CPM with Cyclone. This diagram contains three components: resources, activities and their connections. The general network is divided into sub-networks. Each subnet contains the three components and its number of repetitions. Although the simulation adapts perfectly to linear activities, the graphical representation, independent of activities and resources, for large networks becomes too complex. [16] developed the Repetitive Scheduling Method RSM. This method combines the advantages of LSM, thus, it promotes the continuity of the use of resources and accepts variable progress rates and CPM, thus it demonstrates the relationships between activities and it can graphically present the activities in parallel.

3. Repetitive Projects

Modelling repetitive projects [17] is designed to plan projects where tasks are repeated and assigned from unit to unit, floor to floor, or area to area. Resources move around to repeat the same tasks. This differentiates them from linear projects, in which machines run continuously. The main objective of repetitive projects is the constant use of resources. A model is resource-based, in which the availability of resources determines the dependencies between tasks. This feature distinguishes it from the traditional Gantt-Procedure chart, which is primarily oriented by constraints between activities. The rate of progress of operations is linearized to ensure smooth execution. The number of shifts required is calculated by the quotient of the time required to complete a single unit by the total time available to complete the work of that specialty for all units, to ensure linearity of execution.

Repetitive methods can model vertical projects, such as multi-story buildings, and horizontal projects, such as the construction of several similar units. The approach uses two presentation axes. The x-axis represents time and the y-axis models the units, floors and areas to be built. The activities/resources are represented graphically by an independent entity that can use the quantities to be executed as an internal measure. This strategy supports both activity and resource-oriented planning.

4. Space Planning Techniques

Space Planning Techniques schedule projects by combining space and time. Most work on space planning has focused on mathematical, deterministic or stochastic optimization techniques. Statistical methods [18, 19, 20] ignore the possible reuse of site space. While dynamic optimization techniques [21, 22, 23, 24] allow it. These purely algorithmic solutions are not too suitable for optimizing site operations, which are very complex. The number of parameters to consider is quite large. In addition, some parameters depend on site circumstances or management decisions. This makes the cost of modelling disproportionate to the benefits. Thus, this paper argues that graphical solutions are more suitable for this type of optimization and can be considered as decision support systems. For this, the bibliographical search cites only the researches which have contributed to the advancement of the graphic modelling.

New planning techniques, based on graphical approaches that use the spaces as principal parameter, appeared in the 1990s. [25] presented a construction space model which defines a collection of descriptive space types and typical models space utilization in the construction of multi-storey buildings. The model identifies 12 uses and patterns of space for construction activities. In 1997, [26] presented the methods of planning the specific spaces necessary for the activities and introduced the sequence of work for which the spaces will be occupied and the spatial conflicts for the construction of multi-storey buildings. [27] proposed a knowledge-based system for planning repetitive work in multi-stage projects. [28] formalized and automated a method of spatial-temporal conflict analysis to help construction managers proactively manage spatial conflicts between activities on their sites.

The Chronographic method [29] for planning building construction projects is a spatiotemporal approach that promotes the modelling of repetition in the execution of works in order to optimize the use of construction sites. This approach prioritizes the planning of critical resources and spaces over the critical path theory. Francis [30] defined the conceptual framework, the graphic protocol, the processes, the logical constraints, and the association and organization models [31]. A scheduling method that presents the same site information using compatible models. The planner can switch from one approach to another by manipulating the graphical parameters. The graphical optimization of the calendar [32] can therefore be done on the basis of a hybrid concept comprising graphical, procedural, and algorithmic techniques.

5. Combining Repetitive Modelling to Space Planning

Methods based on the Gantt-Precedence logic often neglect the modelling of workspaces, thus causing site congestion, or relaxation [33]. The integration of repetitive and spatiotemporal modelling promotes better use of the construction site [34, 35, 36]. This association supports the continuity of use of spaces and teams, as well as linear production. Team works are modelled on the different areas of the construction site and the activities are planned as attributes of the resources. Ensuring only a linearity of activities is counterproductive. Activities are only critical through resources and spaces. It is the limitation of the latter that determines whether an activity becomes critical. To better model linearity, the Spatiotemporal Chronographical method combines three linearities: resources, spaces, and activities. Thus, this modelling ensures at the same time the linear rotation of the teams and a better occupation of the site.

6. Automate and Standardize Multi-Story Building

For repetitive vertical projects, such as multistorey buildings, most specialties are repetitive, such as floor structures, systems, and finishing, while some other activities are non-repetitive, such as foundation and the roof. In this type of building, a large majority of activities are common from one project to another. Thus, it is plausible to think of establishing standardization in order to create an automated system to support the construction of validated timetables. This standardization will facilitate the automation of schedules, reduce the planning task, and assure validated schedules. Using data from numerous studies, a logical map was created.

Figure 1 shows a logic map for a repetitive vertical project. The x-axis (top of the figure) represents the work specialties coded according to the MasterFormat specification divisions and the y-axis (left of the figure) models the different floors, from the foundation and basements to the penthouses and roof of the building. The logic between the specialties and the activities are represented on the logic map.

At the beginning of the project, the planner defines the number of floors for each repetitive group and their respective zones according to the construction stages (Structure; systems; envelope; space division; finishing, and space closure) and then reviews the specialties and logical constraints. From this information, an automated space-time schedule is produced based on the various chronographical models [30].

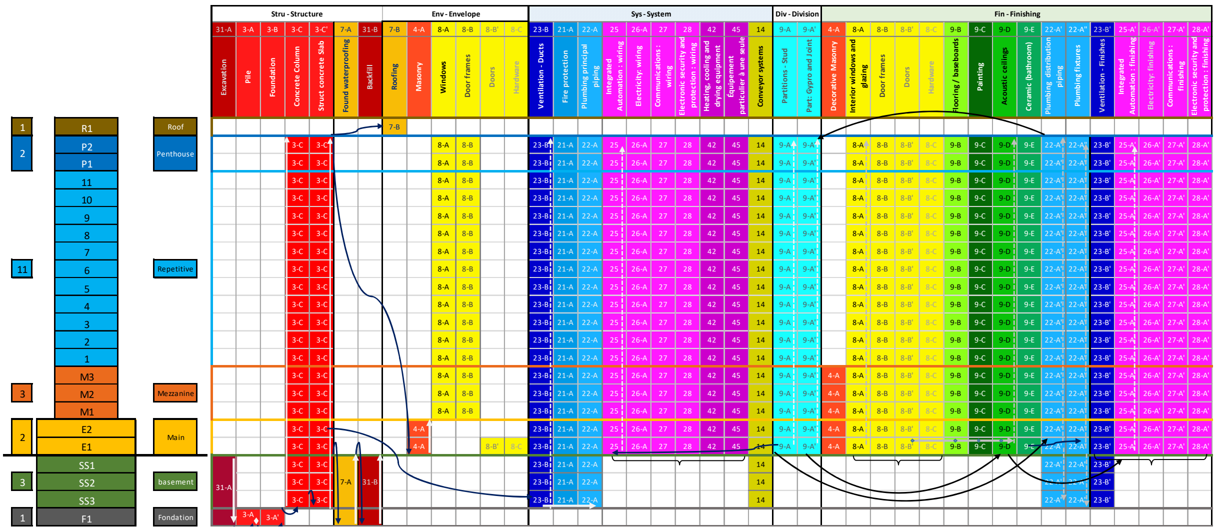

Fig. 1. Logical map for a repetitive vertical project

7. Conclusion

Multi-story building projects are repetitive projects with a large majority of activities in common. A standardization of activities and specialties is therefore a plausible solution. This standardization will facilitate the automation of the schedules, will lighten the planning task, and will ensure validated schedules. Managers will concentrate more on coordinating work sites and optimizing the execution process. The use of graphical models based on repetitive spatiotemporal concepts has a considerable advantage in facilitating visual optimization without requiring complex calculations. Repetitive planning methods integrate space management, operations, and shift rotation from the planning stage. The space-time method combines three linearities: resources, spaces, and activities. By modelling spaces, it is also easier to plan traffic and intermediate inventories.

References

[1] Rahbar, F. and Rowing, J E. (1992). Repetitive activity scheduling process. Proc., AACE 36th Annual Meeting., Orlando, Fla., pp. 0.5.1-0.5.8.
[2] Trimble, G. (1984). Ressource-oriented scheduling. Project Management Journal, Project Management Institute, 2(2), pp. 70-74. https://doi.org/10.1016/S0263-7863(84)80002-2
[3] Khisty, C.J. (1970). The Application of the Line of Balance Technique to the construction industry. Indian Concrete J., 44(7), 297-300, 319-320.
[4] Stradal, O., Cacha, J. (1982). Time Space Schedulling Method. Journal of construction Engineering and management, 108(CO3), pp. 445-457
[5] Johnston, D. W. (1981). Linear scheduling methods for highway construction. Journal of Construction Div. ASCE, https://doi.org/10.1061/jcceaz.0000960, 107(2), pp. 247-261
[6] Mattila, K. G. Park, A. (2003). Comparison of Linear Scheduling Model and Repetitive Scheduling Method. Journal of Construction Engineering and Management 129(1). https://doi.org/10.1061/(ASCE)0733-9364(2003)129:1(56)
[7] Harmelink, D.J. and Rowings, J.E. (1998). Linear Scheduling Model: Development of Controlling Activity Path. Journal of Construction Engineering and Management 124(4). https://doi.org/10.1061/(ASCE)0733-9364(1998)124:4(263)
[8] Harris, R.B., Ioannou, P.G. (1998). Scheduling Projects with Repeating Activities. Journal of construction Engineering and management, https://doi.org/10.1061/(asce)0733-9364(1998)124:4(269) 119, pp. 196-214.
[9] Shoderbeck, P.P., Digman, L. A. (1967). Third generation, PERT/LOB. Harvard Bisness Rev., 45(5), pp. 100-110.
[10] Perera, S. (1982). Network planning of projects comprising repetitive activities. IAHS Conf. On Impact of Economy and Technology, International Association of Housing Science, Vienna Austria, pp. 927-985.
[11] Reda, R. M. (1990). RPM: Repetitive Project Modeling. Journal of Construction Engineering and Management (ASCE). Vol. 116, Issue 2. https://doi.org/10.1061/(ASCE)0733-9364(1990)116:2(316)
[12] Al Sarraj, Z. (1990). Formal Development of Line-of-Balance Technique. Journal of construction Engineering and management, 116(4), pp. 689-704.
[13] Thabet, W.Y., and Beliveau, Y.J. (1994). Modeling work space to schedule repetitive floors in multistory buildings. Journal of Construction Engineering and Management 120(1), 96-116. https://doi.org/10.1061/(ASCE)0733-9364(1994)120:1(96).
[14] Suhail, S. A., Neale, R. H. (1994). CPM/LOB: New methodology to integrate CPM and Line of balance. Journal of construction Engineering and management, https://doi.org/10.1061/(asce)0733-9364(1994)120:3(667) 120, pp. 667-684.
[15] Bolivar and Halpin (1998). Simplified Simulation System for Construction Projects. Journal of Construction Engineering and Management 124(1). https://doi.org/10.1061/(ASCE)0733-9364(1998)124:1(72)
[16] Selinger, S. (1980). Construction Planning for Linear Projects. Journal of the construction Division, ASCE, 106(CO2), pp. 195-205.
[17] Francis, A. (2004). La méthode Chronographique pour la planification des projets de Construction. Ph.D. Thesis (20), (2004) École de technologie supérieure, Montreal, University of Quebec. http://espace.etsmtl.ca/692/ (in French)
[18] Rodriguez-Ramos, W.E. (1982). Quantitative techniques for construction site layout planning. [dissertation thesis]. [Gainesville, FL]: University of Florida.
[19] Tommelein, I.D. (1989). SightPlan - an expert system that models and augments human decision-making for designing construction site layouts. [dissertation thesis]. [Standford (CA)]: Stanford University.
[20] Yeh, I.C. (1995). Construction-Site Layout Using Annealed Neural Network. Journal of Computing in Civil Engineering 9(3), 201-208. https://doi.org/10.1061/(ASCE)0887-3801(1995)9:3(201).
[21] Zouein, P.P., and Tommelein, I.D. (1999). Dynamic layout planning using a hybrid incremental solution method. Journal of Construction Engineering and Management 125(6), 400-408. https://doi.org/10.1061/(ASCE)0733-9364(1999)125:6(400).
[22] Xu, J., and Li, Z. (2012). Multi-Objective Dynamic Construction Site Layout Planning in Fuzzy Random Environment. Automation in Construction 27, 155-169. https://doi.org/10.1016/j.autcon.2012.05.017.
[23] Kumar, S.S., and Cheng, J.C.P. (2015). A BIM-based automated site layout planning framework for congested construction sites. Automation in Construction 59, 24-37. https://doi.org/10.1016/j.autcon.2015.07.008.
[24] Farmakis, P.M., and Chassiakos, A.P. (2018). Genetic algorithm optimization for dynamic construction site layout planning. Organization, Technology and Management in Construction 10, 1655-1664. https://doi.org/10.1515/otmcj-2016-0026.
[25] Riley, D.R., and Sanvido, V.E. (1995). Patterns of construction-space use in multistory buildings. Journal of Construction Engineering and Management 121(4), 464-473. https://doi.org/10.1061/(ASCE)0733-9364(1995)121:4(464).
[26] Riley, D. R., & Sanvido, V. E. (1997). Space planning method for multistory building construction. Journal of Construction Engineering and Management, 123(2), 171-180. https://doi.org/10.1061/(ASCE)0733-9364(1997)123:2(171).

[27] Thabet and Beliveau (1997) Thabet, W.Y., and Beliveau, Y.J. (1997). SCaRC: Space-Constrained Resource-Constrained scheduling system. Journal of Computing in Civil Engineering 11(1), 48-59. https://doi.org/10.1061/(ASCE)0887-3801(1997)11:1(48).
[28] Akinci, B., Fischer, M., and Zabelle, T. (1998). Proactive approach for reducing non-value adding activities due to time-space conflicts, in: 6th Annual Conference of the International Group for Lean Construction. (Guaruja, Brazil: IGLC).
[29] Francis, A. (2013). The chronographical approach for construction project modelling. Management, Procurement and Law 166(4), 188-204. https://doi.org/10.1680/mpal.12.00009.
[30] Francis, A. (2015). Applying the Chronographical approach for modelling to different types of projects. Proceedings of the 5th International/11th Construction Specialty Conference (ICSC 15), Vancouver, BC, Canada, 101(1-9).
[31] Francis, A. (2016). A chronographic protocol for modelling construction projects. Management, Procurement and Law 169(4), 168-177. https://doi.org/10.1680/jmapl.15.00039.
[32] Francis, A. (2019). Chronographical Spatiotemporal Scheduling Optimization for Building Projects. Frontiers in Building Environment 5, 1-14. https://doi.org/10.3389/fbuil.2019.00036.
[33] Chua, Yeoh, and Song, 2010). Quantification of Spatial Temporal Congestion in Four-Dimensional Computer-Aided Design. Journal of Construction Engineering and Management. 136(6). https://doi.org/10.1061/(ASCE)CO.1943-7862.0000166
[34] Akinci, B., Fischer, M., and Kunz, J. (2002). Automated generation of work spaces required by construction activities. Journal of Construction Engineering and Management 128(4), 306-315. https://doi.org/10.1061/(ASCE)0733-9364(2002)128:4(306).
[35] Seppänen, O., Evinger, J., and Mouflard, C. (2014). Effects of the location-based management system on production rates and productivity. Construction Management and Economics 32(6), 608-624. https://doi.org/10.1080/01446193.2013.853881.
[36] Francis, A. (2022). Chronographical Modelling for Repetitive Project. In Creative Construction e-Conference 2022. https://doi.org/10.3311/CCC2022-032

COMPARISON OF OEE-BASED MANUFACTURING PRODUCTIVITY METRICS

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Abstract

Overall Equipment Effectiveness (OEE) is a widely used productivity metric for different pieces of equipment. It provides information on the effectiveness of production, so the percentage of valuable operation time to planned uptime of the machine. The OEE, as the core metric of Total Productive Maintenance (TPM), helps to identify losses in production and quantify operational efficiency allowing actions to be taken that contribute to the continuous improvement of the plant. Despite or perhaps due to its popularity, OEE is not an accurate, well-defined measure. This is because the same considerations cannot be used equally well in different industries or may serve different purposes from one company to another, causing modifications in the calculation and measurement methods. Therefore, the OEE concept may mean other things from company to company, industry to industry. Researchers have tried identifying and overcoming the drawbacks of the original OEE by defining new calculations and creating new metrics. This study aims to overview the indicators available in the literature and compare their advantages/disadvantages. It also seeks to clarify these different definitions, naming conventions, calculation methods, and investigate their usability and the limitations of applicability.

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Keywords: key performance indicator, overall equipment effectiveness, production losses, productivity measurement, total productive maintenance.

1. Introduction

Measuring production efficiency is widespread in all fields of industry, as it can be used to detect various errors and identify hidden capacities. This benefit allows the latent capacities to be exploited, and productivity can be increased without any investment. In addition, increasing efficiency is critical due to today’s rising resource prices and energy reduction directives. For this reason, we dare to suppose, there is no production manager today who does not prioritise production efficiency. The authors of this article attempt to characterise and compare measures of production efficiency developed in recent decades from the original Overall Equipment Effectiveness (OEE) concept to nowadays’ metrics. This study aims to explore the advantages and disadvantages of measures and clarify definitions that are often used inconsistently.

2. Basic OEE calculation

The OEE calculation was originally proposed by Nakajima [1] as one of the main key performance indicators (KPI) for Total Productive Maintenance (TPM). The OEE measurement aims to detect production losses and maximise equipment effectiveness. The production-related losses, often mentioned as “six big losses”, are the following:

Downtime:

- Equipment failure
- Setup and adjustment

Speed losses:

- Idling and minor stoppages
- Reduced speed

Defects:

- Process defects
- Reduced yield

As defined by Nakajima, the OEE is derived from the multiplication of three sub-KPIs (Key Performance Indicator), which focus on the three different types of losses:

$$OEE = Availability \cdot Performance\ efficiency \cdot Rate\ of\ quality$$

The availability refers to the rate of operation time to loading time:

$$Availability = \frac{Operation\ time}{Loading\ time}$$

Due to the purpose of the OEE, the time baseline is not the total available time (e.g., usually one month or one year), but the loading time of the equipment. The loading time does not include scheduled downtimes due to the production plan, as this does not contribute to the operational efficiency of the equipment. Thus, capacity utilisation and traditional capacity indexes are not considered in the OEE calculation. The loading time – so the baseline of the calculation – can be calculated by subtracting the planned downtime from the total available time:

$$Loading\ time = Total\ available\ time - Planned\ downtime$$

The planned downtime includes the planned maintenance time, bank holidays, and the pre-scheduled downtime in the production plan. Operation time counts the exact amount of time when the given equipment is running. Therefore, the loading time can be divided into operation time and equipment downtime, such as breakdown, and setup/adjustment time.

The second component of the OEE is performance efficiency which is the product of the operating speed rate and the net operating rate.

$$Performance\ efficiency = Operating\ speed\ rate \cdot Net\ operating\ rate$$

The operating speed rate refers to the production speed losses. It indicates the differences between the actual and ideal speed or cycle time:

$$Operating\ speed\ rate = \frac{Ideal\ cycle\ time}{Actual\ cycle\ time}$$

The net operating rate takes the minor stoppages into account. The value shows how stable the production is, so it is a comparison between the actual processing time and operation time:

$$Net\ operating\ rate = \frac{Processed\ amount \cdot Actual\ cycle\ time}{Operation\ time}$$

The performance efficiency, as the product of operating speed rate and net operating rate, is the ratio between the ideal time required to produce the given amount and the operation time of the machine. Therefore, it indicates slowdowns compared to the ideal speed and minor stoppages during production:

$$Performance\ efficiency = \frac{Processed\ amount \cdot Ideal\ cycle\ time}{Operation\ time}$$

The rate of quality reflects to the defects, as the time spent producing scrap is wasted time:

$$Rate\ of\ quality = \frac{Processed\ amount - Defect\ amount}{Processed\ amount} = \frac{Processed\ good\ amount}{Processed\ amount}$$

After performing the multiplication, the OEE can be calculated as follows:

$$OEE = \frac{Processed\ good\ amount \cdot Ideal\ cycle\ time}{Loading\ time}$$

It shows how much time would be needed to produce the actually manufactured qualified amount of product under optimal conditions compared to the loading time of the machine. The relations of the OEE defined by Nakajima, the six big losses and the 3 sub-KPIs are summarised in Figure 1.

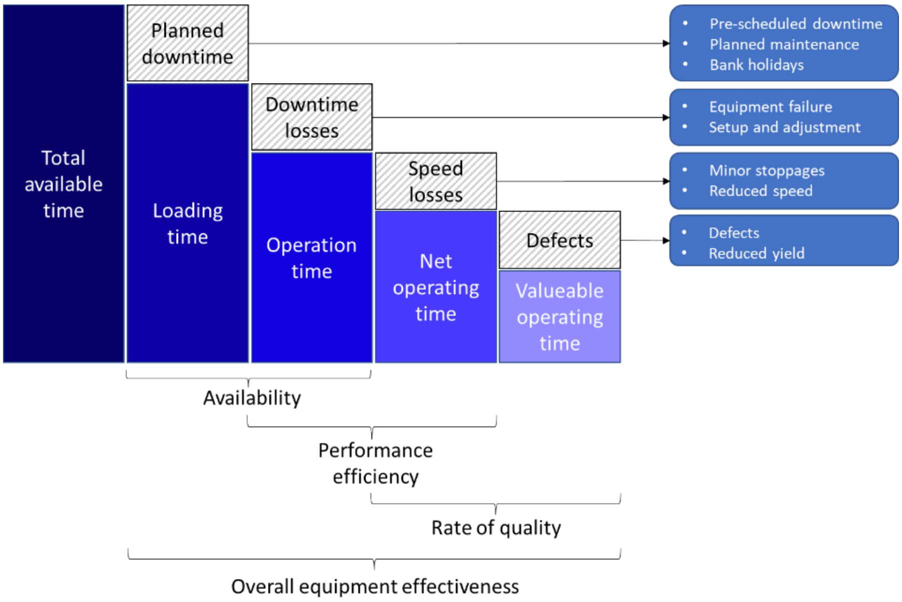

Fig. 1. Overall Equipment effectiveness defined by Nakajima

3. New KPIs based on OEE calculation

The OEE calculation has evolved significantly in the last three decades, leading to new indicators. The reasons for the improvements are manifold. The following section summarises the new measures based on the OEE, investigates the reasons behind the development, and analyses the advantages/disadvantages.

Ames et al. [2] interpreted the OEE calculation for semiconductor manufacturing equipment and defined SEMATECH's approach to Overall Equipment Effectiveness. The main difference from the original concept is that the availability and, therefore, the OEE take the nonscheduled time (e.g., holidays, shutdown) into account. Due to this modification, the time basis of the calculation is the total time instead of the loading time. This change can be particularly beneficial for measuring high-value machines' efficiency, where the nonscheduled periods should be avoided because of the cost of unused capacity. However, this calculation method can be misleading for intermittent or seasonal production, setting unachievable and meaningless goals.

Total Effectiveness Equipment Performance (TEEP) measures the equipment's effectiveness relative to the total time, similar to Ames's OEE calculation. The TEEP calculation also includes another factor, which is utilisation [3]:

$$TEEP = Utilization \cdot OEE$$

where

$$Utilization = \frac{Loading\ time}{Total\ time}$$

So, TEEP indicates the scheduling losses in production as well and is useful for the same cases as Ames's OEE if the production runs 24/7.

The concept of Production Equipment Effectiveness (PEE) [4] for discrete-type production operations is similar to the original OEE by Nakajima. Accordingly, the same three sub-KPIs are included but allow weighting of the individual components. The significant parameters are given a higher weight so that PEE better reflects the critical losses, which are more important for the plant. The calculation method is as follows:

$$PEE = A^{k_1} \cdot P^{k_2} \cdot Q^{k_3}$$

The authors suggest using the analytical hierarchy process (AHP) to determine the appropriate weighting factors.

In the case of continuous process operations, the PEE is a function of availability, attainment, performance efficiency, quality rates, product support efficiency, and operating utility:

$$PEE = A_1^{k_1} \cdot A_2^{k_2} \cdot P^{k_3} \cdot Q^{k_4} \cdot PSE^{k_5} \cdot OU^{k_6}$$

The A_1 availability refers to the scheduled downtime and A_2 attainment reflects the unscheduled downtime. Thus, A_1 and A_2 can be seen as sub-categories of the OEE's availability (A). With this separation, the two indicators can be given different weights. PSE and OU take account of transaction losses and no demand time; however, these can also be calculated as downtimes.

The OEE, despite its name, not only reveals the losses related to the equipment, but also considers the malfunctions and shortages in the environment of the equipment. Losses include not only failures or slowdowns caused by the equipment, but also stoppages and speed losses due to shortages of raw material and workforce, which concerns the organisation of production rather than the equipment itself. This feature was criticised by de Ron and Rooda [5], and they created a new metric, Equipment Effectiveness (E), which focuses solely on the equipment. The authors distinguished equipment-dependent and equipment-independent statuses and defined the effective time, which means when the equipment was able to perform its dedicated production task. The effective time excludes the equipment-independent causes and the duration of this status. The base of the Equipment Effectiveness (E) is the effective time. Thus, this KPI excludes production losses that cannot be closely linked to the operation of the equipment, which can be both an advantage and a disadvantage. On the one hand, it can be an advantage, e.g., the maintenance team, who are only concerned with the breakdowns and settings of the equipment. However, for coordinators, whose job is to manage the whole production, this KPI can mask severe errors, which is disadvantageous.

Hung et al. [3] defined new OEE-based KPIs, the value-added OEE and value-added TEEP (VAOEE and VATEEP). Common to both metrics, the original ones are multiplied by a design factor, which describes the design cycle. The production cycle can be divided into value-added and non-value-added sub-processes, and the ratio of the value-added steps to the whole cycle is the design factor:

$$Design = \frac{Value\text{-}added\, time\ in\ a\ design\ cycle}{Design\ cycle\ time}$$

Thus, the VAOEE can be calculated as follows:

$$VAOEE = OEE \cdot Design = \frac{Processed\ good\ amount \cdot (Value\text{-}added\, time\ in\ a\ design\ cycle)}{Loading\ time}$$

The authors questioned the assumption that the design cycle is the shortest possible time. If this approximation is not met, the OEE-based developments have limitations, and hidden capacities remain in production despite the maximised OEE. Nevertheless, process optimisation cannot significantly impact production efficiency if the original OEE-related losses are enormous. Alternatively, in some fields of industry, due to the nature of manufacturing, it is difficult to bypass or omit some non-value-added but necessary steps.

Some KPIs derived from OEE target not only operational efficiency but also include financial implications. The Overall Resource Effectiveness (ORE) broadens the scope of OEE with the value of resources [6]. ORE is the ratio of recovered investment (output) to the overall investment (input).

The inputs are split into two groups, namely the material and resource inputs required to run the process. Both types of inputs have an efficiency parameter: the first one is material efficiency, and the second one is the OEE. Material efficiency evaluates how efficiently the raw materials are transformed, while the OEE, in this interpretation, measures how efficiently the production-related resources are used. The ORE combines these two aspects of the production and can be calculated with the following expression:

$$ORE = \frac{OEE \cdot PIMV + M \cdot MIMV}{PIMV + MIMV}$$

Where the process input monitoring value (PIMV) and the material input monitoring value (MIMV) represent the economic investment in materials and resources to sustain a process. The ORE focuses not only on production effectiveness, but also on the value of the components involved in manufacturing, making it both an operational and financial KPI.

Wudhikarn et al. [7] argued that the OEE is unsuitable for benchmarking and prioritising because it neglects the different capacities of the machines, the production cost, and the product's value. Without these considerations, the focus can be inappropriate, as the impact of operational losses in the money dimension is not equal for different pieces of equipment. The OECL calculation considers the opportunity cost and the production cost as well. With OECL, production inefficiencies can be translated into cost, making it more transparent for financial managers. This approach was further developed by combining it with the cost of quality, resulting in the Overall Equipment Quality Cost Loss (OEQCL) [8].

Several authors have extended the understanding of the OEE from the machine level to the manufacturing line level or even to the whole plant, factory level. In general, machines are not independent of each other, and are not stand-alone pieces of equipment. The previous or next machine often influences the given machine in the manufacturing line. Therefore, it is more suitable to measure the effectiveness of the whole line instead of calculating the individual machines' OEE one by one. It is possible with the concept of Overall Line Effectiveness (OLE) [9]. In this KPI, the availability is replaced by the line availability (LA) and the performance efficiency is merged with the rate of quality resulting in the line production quality performance efficiency $(LPQP)$:

$$OLE = LA \cdot LPQP$$

The line availability is calculated from the nth (last) machine's operating time and the planned line loading time. While the $LPQP$ can be obtained from the processed good amount by the nth machine (G_n), the cycle time of the bottleneck machine (which is the largest cycle time) (CYT_{bn}) and the operating time of the 1st machine (OT_1):

$$LPQP = \frac{G_n \cdot CYT_{bn}}{OT_1}$$

The equation can be used to calculate the line effectiveness. However, it has to be highlighted that this relation is only applicable in that case, when the machines are connected in series, the line is continuous (no buffers), and the operating time of the previous equipment is the loading time of the following equipment in the series.

Braglia et al. [10] criticised the OLE metric as it only focuses on the last machine in the manufacturing line, making it hard to recognise where the main criticalities occur. They proposed a new metric, namely the Overall Equipment Effectiveness of a Manufacturing Line (OEEML). The OEEML can be calculated from the good amount processed by the nth machine, the bottleneck cycle time (CYT_{bn}) and the line loading time (LLT):

$$OEEML = \frac{G_n}{\frac{LLT}{CYT_{bn}}}$$

Scott and Pisa [11] proposed the Overall Factory Effectiveness (OFE), which is a factory-level OEE-based KPI. They did not publish a well-defined metric to measure plant efficiency, considering that different companies and factories have other goals [12]. So, they proposed that the firms build their own

OFE measures by combining metrics that are important for them. These KPIs can be, for example, the OEE, capacity utilisation, yield, and ramp-up performance.

One possible OFE metric was announced by Huang et al. [13], the Overall Throughput Effectiveness (OTE). The OTE can be calculated on a given time period as

$$OTE = \frac{Good\ product\ output\ from\ factory}{Theoretical\ attainable\ product\ output\ from\ factory\ in\ total\ time}.$$

The OTE can be determined for different types of sub-systems, such as machines in series or parallel. Then, the OTE for the sub-systems can be used to calculate the OFE level indicator.

4. Conclusion

The advantages and disadvantages of the above metrics are discussed below. More precisely, it is impossible to present pro-contra properties since the same feature of a given efficiency indicator is advantageous in some cases and disadvantageous in other applications. Therefore, discussing industrial applications rather than benefits and drawbacks is more beneficial.

Table 1. shows the KPIs presented in the article, grouped into five categories based on how the original OEE was modified. The main features are also summarised in the table.

Table 1. Presented KPIs' main features.

Modification of OEE	KPIs	Main feature
Reallocate/extend the production-related time	Ames's OEE	Utilisation is part of the calculation
	TEEP	
	E	Omits the non-machinery losses
	VAOEE/VATEEP	Considers the value-added/non-value-added steps
Weighting components	PEE	Allows weighting
Considering financial aspects	ORE	Value of resources is part of the calculation
	OECL	Calculates with the opportunity cost and production cost loss
	OEQCL	OECL extended with the cost of quality
Extending to line level	OLE	Shows the efficiency of the production line without buffers
	OEEML	Shows the efficiency of production lines with buffers
Extending to plant level	OFE	Product of different KPIs
	OTE	It is calculated from the production sub-systems of the factory

These key properties determine the usability of each metric. They can be used to decide which indicator is appropriate considering the production parameters.

Ames's OEE and the TEEP are technically the same. The baseline of the calculation is the total time. Using total time as baseline is advantageous when the production is 24/7 or if the machine is high-value, highly automated. In this case, the cost of unused capacity would be very high if there were much unscheduled time on the machine.

The Equipment Effectiveness (E) focuses solely on the machine and not on external factors affecting it, as it excludes the machine-independent losses from the calculation. It can be useful for the maintenance department of the firm, but not for production managers.

VAOEE and VATEEP allow a higher resolution by also analysing the cycle time that is considered ideal. These metrics can be helpful when the original OEE can no longer be realistically improved. In some industries, such as pharmaceuticals, where there are many processing and purification steps in addition to a main process, it is impossible to leave out the necessary but non-value-added steps. Consequently, VAOEE/VATEEP cannot be raised above a certain level.

PEE allows the inherent OEE components to be weighted resulting in a measure that focuses more/less on different problems. It is advisable to use it when, for example, there is a known high-impact loss to which the plant wants to pay more attention.

ORE, OECL, OEQCL consider financial aspects as well. The ORE calculates with the value of the resources, which allows e.g. scrap or rework to be expressed in monetary dimension rather than just in time. It is thus possible to show that the same time losses have different financial impacts depending on the product's value. OECL can also show opportunity costs and production cost losses. The OEQCL is further extended with the cost of quality. With these changes, the OEE production indicator has become a financial KPI, which can be a valuable indicator for strategic decisions and the financial department of the company.

OLE and OEEML are production line-level indicators. While OLE does not, OEEML allows the use of buffers between machines. These indicators measure the performance of the whole line. This is particularly useful where machines are highly interdependent, where it makes no sense or is not even possible to describe the performance of just one single piece of equipment.

In addition, OFE is an even higher-level metric, as it can describe the factory performance. It is a product of different KPIs and less well-defined than the KPIs discussed so far. On the one hand, it is advantageous that each company can define its own plant-level indicator. However, it is not suitable for benchmarking between companies. A well-defined OFE metric is the OTE. The OTE can be used to describe the efficiency of each sub-system, which can be summed to obtain the efficiency of the factory; althought, the calculation for large systems can be complex. Another disadvantage of higher-level indicators is that the more information they are composed of, the more difficult it is to see the actual content.

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References

[1] S. Nakajima, *Introduction to TPM*. Portland, Oregon, USA: Productivity Press, 1988.
[2] V. A. Ames, J. Gililland, J. Konopka, R. Schnabl, and K. Barber, "Semiconductor Manufacturing Productivity Overall Equipment Effectiveness (OEE) Guidebook Revision 1.0," 1995.
[3] Y. H. Hung, L. Y. O. Li, and T. C. E. Cheng, "Uncovering hidden capacity in overall equipment effectiveness management," *International Journal of Production Economics*, vol. 248, pp. 108494, Jun. 2022, doi: 10.1016/j.ijpe.2022.108494.
[4] A. Raouf, "Improving Capital Productivity through Maintenance," *International Journal of Operations Production Management*, vol. 14, no. 7, pp. 44–52, Jul. 1994, doi: 10.1108/01443579410062167.
[5] A. J. de Ron and J. E. Rooda, "Equipment Effectiveness: OEE Revisited," *IEEE Transactions on Semiconductor Manufacturing*, vol. 18, no. 1, pp. 190–196, Feb. 2005, doi: 10.1109/TSM.2004.836657.
[6] J. A. Garza-Reyes, "From measuring overall equipment effectiveness (OEE) to overall resource effectiveness (ORE)," *Journal of Quality in Maintenance Engineering*, vol. 21, no. 4, pp. 506–527, Oct. 2015, doi: 10.1108/JQME-03-2014-0014.
[7] R. Wudhikarn, C. Smithikul, and W. Manopiniwes, "Developing Overall Equipment Cost Loss Indicator," in *Proceedings of the 6th CIRP-Sponsored International Conference on Digital Enterprise Technology*, pp. 557–567, 2010, doi: 10.1007/978-3-642-10430-5_43.
[8] R. Wudhikarn, "Improving overall equipment cost loss adding cost of quality," *International Journal of Production Research*, vol. 50, no. 12, pp. 3434–3449, Jul. 2011, doi: 10.1080/00207543.2011.587841.
[9] R. M. Nachiappan and N. Anantharaman, "Evaluation of overall line effectiveness (OLE) in a continuous product line manufacturing system," *Journal of Manufacturing Technology Management*, vol. 17, no. 7, pp. 987–1008, Oct. 2006, doi: 10.1108/17410380610688278.

[10] M. Braglia, M. Frosolini, and F. Zammori, “Overall equipment effectiveness of a manufacturing line (OEEML): An integrated approach to assess systems performance,” *Journal of Manufacturing Technology Management*, vol. 20, no. 1, pp. 8–29, Dec. 2008, doi: 10.1108/17410380910925389.
[11] D. Scott and R. Pisa, “Can Overall Factory Effectiveness Prolong Moore’s Law?,” *Solid State Technology*, vol. 41, no. 3 pp. 75, Mar. 1998.
[12] R. Oechsner, M. Pfeffer, L. Pfitzner, H. Binder, E. Müller, and T. Vonderstrass, “From overall equipment efficiency (OEE) to overall Fab effectiveness (OFE),” in *Materials Science in Semiconductor Processing*, vol. 5, no. 4–5, pp. 333–339, Aug. 2002, doi: 10.1016/S1369-8001(03)00011-8.
[13] S. H. Huang *et al.*, “Manufacturing productivity improvement using effectiveness metrics and simulation analysis,” *International Journal of Production Research*, vol. 41, no. 3, pp. 513–527, Jan. 2003, doi: 10.1080/0020754021000042391.

DATA ACQUISITION SYSTEM FOR AUTOMATED UPDATING OF PRECAST CONCRETE PROJECT SCHEDULE

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Abstract

In the construction project execution phase, the decision-making process greatly relies on quality and timely data acquisition. The comparison analysis approach, i.e., as-planned vs as-built, is common for progress tracking in construction projects. This approach requires continuous real-time data acquisition from the construction site for further integration into a construction schedule for progress analysis. Due to the complex and dynamic environment on the construction site, the main goal of data gathering efficiency increase lies in its automation. This paper presents a data acquisition system for automated updating of the precast concrete project schedule. The system is BIM-based, in which data collected from the construction site, i.e., actual starts and actual finishes of assembled elements, are automatically transferred and integrated into the project schedule. In the BIM environment, each element is uniquely determined by its work breakdown structure (WBS) code, which corresponds to its quick response (QR) code in the project schedule attached to the element on the construction site. The first discrete scan of the code on the construction site marks the actual assembly start of an element, and upon its assembly, the last discrete scan marks its actual finish. The system automatically transfers the data into the project schedule and updates the following assembly activities. The system was applied to a precast concrete project case study in laboratory conditions. The system performed smooth and efficient data collection, transfer, and integration into the BIM environment.

Keywords: automation, BIM, data acquisition, precast concrete project, schedule update.

1. Introduction

The decision-making process throughout the execution phase of a construction project primarily depends on prompt and quality data acquisition, wherefore construction progress monitoring and timely schedule updates are essential for project success. Construction projects are commonly deadline- and budget-oriented, whilst unfortunately reports constantly show that over 53 % of projects are behind schedule while over 66 % have experienced cost overruns [1]. The lack of efficiency and accuracy in construction progress monitoring is found to greatly aid to aforementioned issues. Continuous construction progress monitoring is essential for finding discrepancies between the as-planned (AP) and as-built (AB) states for swift implementation of the necessary corrective actions [2]. Since the construction sector is prone to traditionalism, it is common practice to adopt time-consuming, slow-moving, error-prone, and frequently redundant progress reporting procedures that hinder stakeholders from taking proactive actions. Instead of providing the crucial real-time update, such progress monitoring approaches are based on labor-intensive and manual information gathering, documenting, and reporting procedures [3]. Project success depends on the timely, accurate, and effective collection of monitoring data. Therefore, choosing useful data acquisition and detection methods for construction progress monitoring is particularly significant since it ensures data dependability and minimizes plausible errors [1]. Contemporary information and automation technologies are highlighted as an efficient alternative on construction sites due to the complex and dynamic environment therein. In this context, three primary types of advanced technologies standout, i.e., laser-based methods, tag-based methods, and image-based methods, which have been introduced and successfully utilized for data acquisition on construction sites [4]. As usual for construction project planning, precast project schedules are sensitive to uncertainties due to the required high level of coordination and interdependences among the activities. It is crucial to assess the schedule in terms of project and activity duration while also keeping track of the progress being made in order to prevent actual project delays [5]. Moreover, precast elements can be located using geospatial tracking technologies, which allow interactions with physical assets through communication with tags or sensors [6]. There are two types of geospatial asset tracking technologies that are frequently used in the construction industry: Quick Response (QR) codes and radio frequency identification (RFID).

Considering the suggested research directions and technologies, the authors propose a system for automated schedule updating of precast concrete projects which is tested in the laboratory conditions. The system’s main goal is to automatically record the assembly of a precast concrete construction in real-time, where the monitoring is object-oriented. The system is aimed to be user-friendly, but swift and efficient tool for AB data acquisition while ensuring a bi-directional input/output data transfer between the cyber (nD BIM model) and physical (construction site) segments of the project. The rest of the paper is structured as follows: the second part presents a concise literature review of relevant research on the subject matter. The third part presents the research methodology, in the fourth part, there are discussions and conclusions.

2. Literature review

One of the pioneers in automating the construction monitoring was reported in 2000, when the authors Abeid and Arditi [7] developed a system for planning and controlling construction progress named Photo-net. It was an automated real-time monitoring system with an object-oriented programming focus that was created in the Delphi environment. The system time-linked sequences of photos taken by a stationary camera (i.e., time-lapse) into films of construction activities and generated graphs using the critical path method. Time-lapse films recorded by cameras installed on the construction site could later be used to compare the planned and realized states of completion. The system's primary drawbacks, according to the authors, are the use of a single stationary camera with constrained frame rates and the requirement for manual recording of activity progress. Authors Dawood et al. [8] carried out a study in 2002 on the automation of a communication system that would allow information sharing among project members. The study's findings revealed savings in working hours of over 90 %, which also resulted in significant savings in total costs. Furthermore, it was estimated that the system provided time savings of over 98 % for the entire registry of technical documentation and its distribution process. In 2003, Abeid et al. [9] developed PHOTO-NET II, as an enhancement of the Photo-net system. PHOTO-NET II utilized the technology in long and complex construction projects on personal computers and presented a novel idea in time-lapse photography that allowed users to alter frame frequencies. The need for automating the updating of schedules was emphasized in 2005 in the paper [10], where the need for recording, transferring, and storing data to assess the completion of the project was shown in the example of a highway construction site. It was detected that the most significant problems were related to recording quantitative data, especially those requiring measurements or calculations. To get around the shortcomings of earlier RFID and global positioning system (GPS) technologies, authors Jang and Skibniewski [11] created a tracking system that combined radio frequency and ultrasound to localize materials. Steel supports, precast concrete elements, and polyvinyl chloride (PVC) pipes were highlighted in this research.

Despite the earlier stated necessity, initiatives to automate schedule updates only started to develop years later. In 2012, a system for automating the monitoring of construction progress that incorporated 4D modeling, laser scanning, and data gathered on the construction site was presented by the authors Tang et al. [12]. Previous methods of schedule updating were based on direct manual data entry into the plan, which is still largely present today. In 2013, authors Kim et al. [13] introduced an automated 4D computer-aided-design (CAD) model update technique using automated project planning, comprising construction site image gathering, construction progress identification, and 4D CAD development. In 2018, a method for automated continuous monitoring of construction progress that used multiple 3D scans on the construction site in real-time was presented by the authors Pučko et al. [14]. The presented system was based on a comparison between the 4D BIM models for the designed and constructed buildings, where the point clouds were gathered using the workers' helmets. According to the authors, to achieve automated partial point cloud registration, worker helmets should feature a subsystem for precise positioning and orientation. In paper [15], a system for automated plan updating using data from 4D BIM models combined with a 3D point-cloud recorded on the construction site was presented and tested on a simple reinforced concrete building. Similar approach utilizing the 4D BIM model was used in [16] where the element's progress data was incorporated into the BIM model, and the elements were colored depending on their expected and actual progress. Also, activity durations dates have been updated by updating the activities actual starts and finishes.

Nowadays, unmanned aerial vehicles (UAV) are increasingly being used to collect construction site information. Hence, a study that employed drones to track the development of an office building was carried out in 2020 [17]. The technique was based on the identification of the building's structural components, including a cross-section approach, an estimation of the volume of the concrete, measurements of height and distance, and defect detection. Data gathering, data processing, and data analysis were the primary components of the procedure, which was shown to be effective. As one of the most widely used technologies today, the real-time data collection technique of using QR codes is also recognized in the construction industry. Its benefits and possibilities of usage were analyzed in multiple papers regarding construction site monitoring, element production processes, material logistics, etc. Using RFID technology, Lanko et al. [18] proposed in 2018 usage of the blockchain in the logistics of construction materials. The authors used the production and transportation of ready-mixed concrete as an example and discovered that using RFID and blockchain technology together will greatly lessen human influence and erroneous information. They have also proposed the use of QR codes instead of RFID due to their affordability and availability on widely used smartphones. In 2019, Zhang et al. [19] proposed a smart hard-hat system for monitoring non-hard-hat use (NHU). The NHU detection system was able to identify the user's personal information and connect it to a specific worker to correlate the NHU detection record with the individual's personal information. After the users sign into the smartphone app with a username and password and tie the smartphone app to the hard hat using a QR code, they can access these features. A mechanism for fusing QR code tracking outputs of the as-built state with the as-planned state in smart contracts was presented by Groesen and Pauwels [6] in 2022. The authors created a fully functional mobile QR-code application to let construction stakeholders gather and manage physical asset data. They contend that this approach is better since designing a QR-code application takes less time than designing an RFID application.

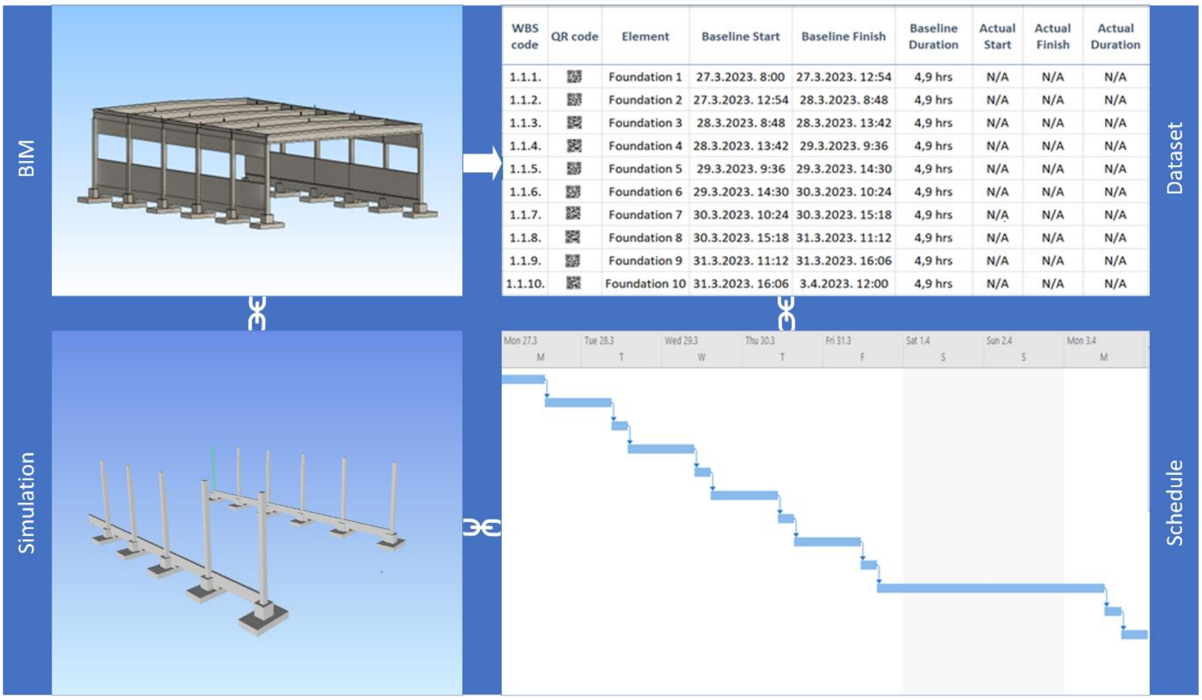
It is necessary to point out here that the approaches have shown various examples of QR code application in the construction industry, even in construction monitoring, but none of them have used them as a tool for automated construction schedule updating.

3. Methodology

3.1. Baseline 4D BIM

The baseline 4D BIM modelling phase initializes the cyber segment of the cyber-physical system of the data acquisition system for automated updating of the precast concrete project schedule. It consists of a BIM model of a precast concrete structure, its baseline schedule, and simulation-ready model as shown in Fig. 1. From the BIM model elements with their information (i.e., WBS codes, list of elements, and physical characteristics) are exported to a spreadsheet prepared model (i.e., dataset), which is dynamically linked with the baseline schedule and simulation model. Such order provides a dynamic connection between the mentioned system’s segments.

As common for the realization phase of a construction project, the BIM model should be structured with a level of detail at least 400. This is because it contains comprehensive details regarding every system and component inside the project, including fabrication, assembly, installation, accurate dimensions, material specifications, installation details, and connections. Due to the characteristics mentioned above, it is possible to perform accurate take-offs, clash identification, and other evaluations that could enhance project results. It is also important to add here that the object-oriented work-breakdown-structure (WBS) codes in the BIM model and in the baseline schedule should uniquely correspond. This dataset also merges the unique WBS code of each precast element with its corresponding unique QR code. The process flow of the whole system is shown in Fig. 2.



WBS code	QR code	Element	Baseline Start	Baseline Finish	Baseline Duration	Actual Start	Actual Finish	Actual Duration
1.1.1.		Foundation 1	27.3.2023. 8:00	27.3.2023. 12:54	4,9 hrs	N/A	N/A	N/A
1.1.2.		Foundation 2	27.3.2023. 12:54	28.3.2023. 8:48	4,9 hrs	N/A	N/A	N/A
1.1.3.		Foundation 3	28.3.2023. 8:48	28.3.2023. 13:42	4,9 hrs	N/A	N/A	N/A
1.1.4.		Foundation 4	28.3.2023. 13:42	29.3.2023. 9:36	4,9 hrs	N/A	N/A	N/A
1.1.5.		Foundation 5	29.3.2023. 9:36	29.3.2023. 14:30	4,9 hrs	N/A	N/A	N/A
1.1.6.		Foundation 6	29.3.2023. 14:30	30.3.2023. 10:24	4,9 hrs	N/A	N/A	N/A
1.1.7.		Foundation 7	30.3.2023. 10:24	30.3.2023. 15:18	4,9 hrs	N/A	N/A	N/A
1.1.8.		Foundation 8	30.3.2023. 15:18	31.3.2023. 11:12	4,9 hrs	N/A	N/A	N/A
1.1.9.		Foundation 9	31.3.2023. 11:12	31.3.2023. 16:06	4,9 hrs	N/A	N/A	N/A
1.1.10.		Foundation 10	31.3.2023. 16:06	3.4.2023. 12:00	4,9 hrs	N/A	N/A	N/A

Fig. 1 4D BIM database

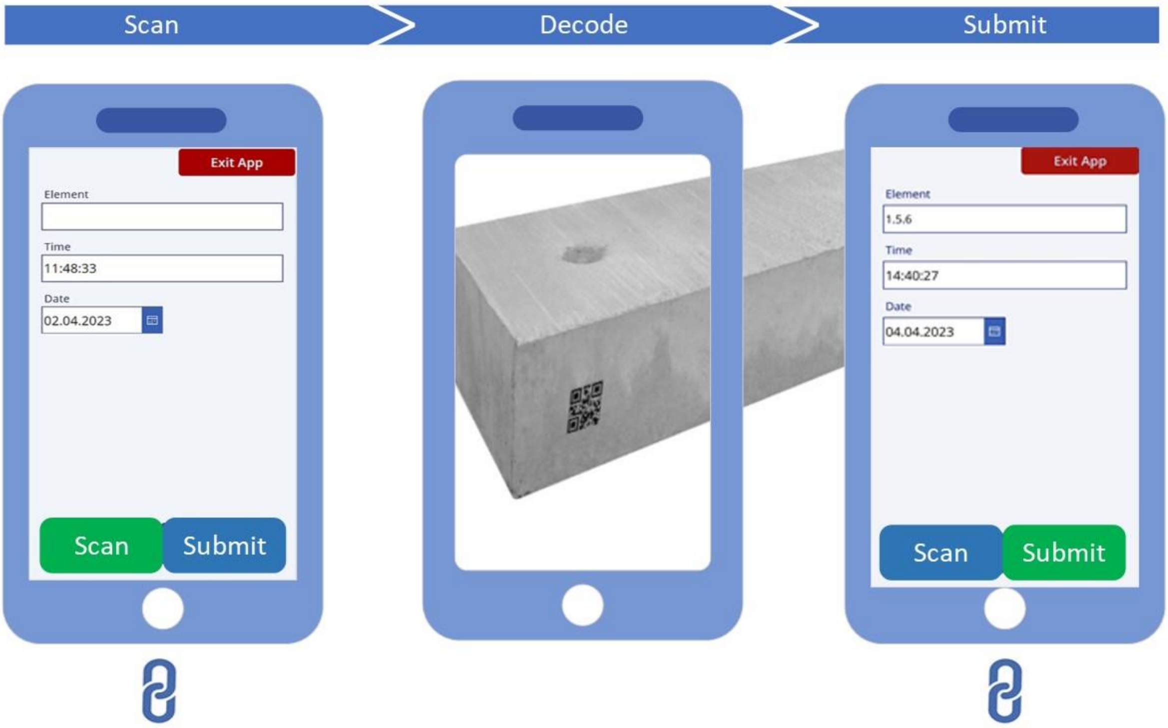
3.2. Construction

The construction execution phase initializes the physical segment of the cyber-physical system of the data acquisition system for automated updating of the precast concrete project schedule. This segment includes the assembly of the precast concrete construction and the monitoring. Monitoring of the construction site in this context requires that the unique QR codes are assigned to each construction element prior to the assembly. This can be done using adhesive stickers or ideally by embedding the codes directly into the element during the manufacturing process. Either way, during the construction phase, it is important to ensure that the QR codes are not damaged or obscured for the system to function properly.

Fig. 2. Process flow of data acquisition system for automated updating of precast concrete project schedule

3.3. Data acquisition

The data acquisition in the execution phase corresponds to the physical segment of the cyber-physical system of the data acquisition system for the automated updating of the precast concrete project schedule. During this phase, a mobile phone application developed for this purpose decodes the QR codes attached to the precast concrete construction elements. The precast concrete element WBS code, the date, and precise time are all obtainable by decoding of each QR code. The application was developed using Microsoft Power Apps [20], with a simple user interface. By pressing the scan button, the phone camera scans the QR code of an element and decodes the Element (i.e., WBS code), Time (i.e., start or finish of the assembly), and Date fields (i.e., date of the assembly), whereas the Submit button sends the scanned data to a specified spreadsheet as presented in Fig. 3.



WBS code	QR code	Element	Baseline Start	Baseline Finish	Baseline Duration	Actual Start	Actual Finish	Actual Duration
1.5.3.		Beam 3	18.4.2023. 10:54	18.4.2023. 13:06	2,2 hrs	19.4.2023. 9:39	19.4.2023. 11:50	2,18 hrs
1.5.4.		Beam 4	21.4.2023. 11:18	21.4.2023. 13:30	2,2 hrs	21.4.2023. 12:03	21.4.2023. 14:15	2,2 hrs
1.5.5.		Beam 5	18.4.2023. 13:06	18.4.2023. 15:18	2,2 hrs	18.4.2023. 13:10	18.4.2023. 15:30	2,33 hrs
1.5.6.		Beam 6	18.4.2023. 15:18	19.4.2023. 8:30	2,2 hrs	18.4.2023. 15:35	18.4.2023. 17:15	1,67 hrs
1.5.7.		Beam 7	24.4.2023. 11:36	24.4.2023. 13:48	2,2 hrs	N/A	N/A	N/A
1.5.8.		Beam 8	19.4.2023. 8:30	19.4.2023. 10:42	2,2 hrs	N/A	N/A	N/A
1.5.9.		Beam 9	24.4.2023. 13:48	24.4.2023. 16:00	2,2 hrs	N/A	N/A	N/A

Fig. 3. Workflow of the data acquisition

3.4. Data processing

Upon the decoded QR code in the data acquisition phase, the corresponding information (i.e., date and time of the actual start or finish, and the WBS code) is submitted to the spreadsheet, where an analysis of the data is performed. The spreadsheet is also used in the baseline 4D BIM modelling phase for generating the QR codes, enabling all the processes to be performed in the closed, circular environment of the system. The spreadsheet is modelled in such a way that the first discrete scan of the QR code on the construction site marks the actual assembly start of an element, and upon its assembly, the last discrete scan marks its actual finish. The actual assembly start, and the actual assembly finish are further used for the calculation of the actual duration of an assembly activity. This calculation considers the duration of the daily work shift and the non-working holidays, finally providing the actual duration of an activity in hours.

3.5. Data analysis

In this phase the previously obtained actual durations of activities in hours are transferred using a dynamic link between the spreadsheet and the project planning software in which the baseline precast concrete structure schedule is updated (shown in Fig. 3.). This automatizes the schedule update and allows a direct comparison between the baseline precast concrete structure schedule and the updated schedule based on the actual data collected. As shown in Fig 4. it is possible to see the updated schedule, executed activities, i.e., which have obtained the actual start, finish, and duration, as well as the following activities which have not been executed yet. Any delays, inefficiencies, or other problems that can affect the project's timeline can be found using this analysis. The data analysis stage is, in general, a crucial part of the cyber-physical system of the data acquisition system for automated updating of the precast concrete project schedule, allowing for real-time updates and adjustments to the project plan based on actual progress and data gathered during the construction phase.

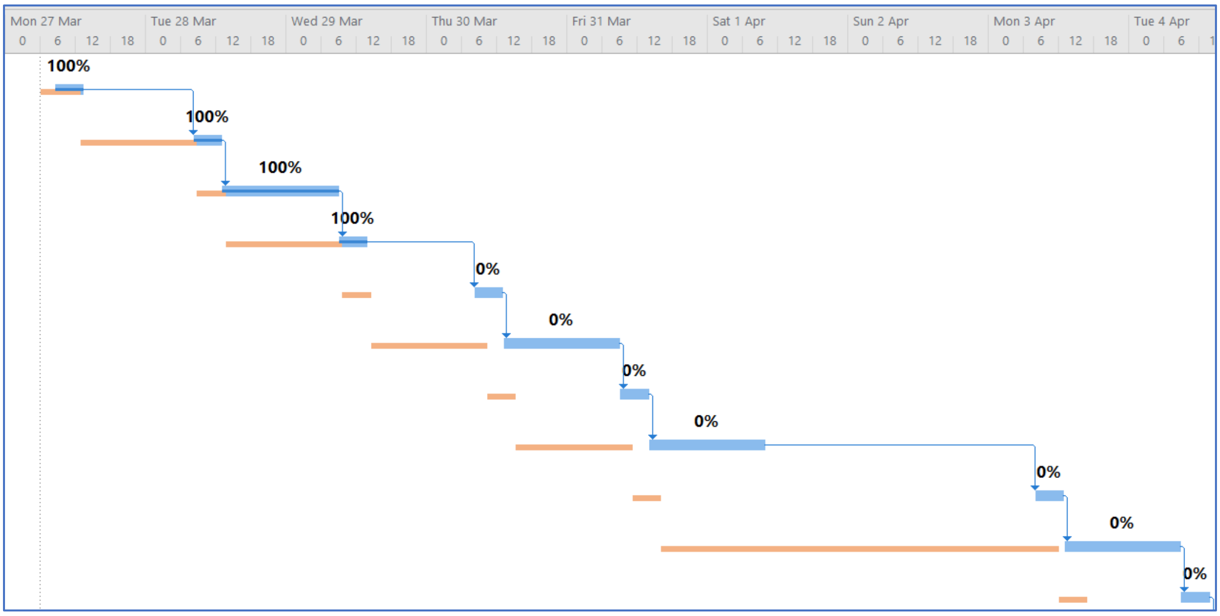


Fig. 4. Updated schedule based on collected data

3.6. Updated 4D BIM

The initial baseline 4D BIM is updated using the data from the previous data analysis phase, therefore updating the initial baseline schedule. Besides, this phase also offers a simulation-ready model to simulate the updated 4D BIM and its actual construction schedule and sequence. With the most recent data and an accurate reflection of the project's development, the updated 4D BIM offers a visual representation of the construction process. Construction managers may better comprehend the project and identify any possible conflicts that might emerge during the following construction by using the updated 4D BIM. By incorporating real-time data and providing a visual representation of the construction project, it allows to make more informed decisions.

4. Discussion and conclusion

This paper presents a data acquisition system for automating precast concrete project schedule updates. Prior research on automated construction schedules has shown various possibilities and technologies. Also, research on QR codes in the construction sector has shown that they can be used for various purposes. To our knowledge, no study has yet demonstrated their use in automating the schedule update process, i.e., the combination of these two research topics. The system is in development and has been tested in laboratory conditions, where it has proven to be efficient, functional, and user-friendly. Besides automating the update process of an assembly schedule, system's premise is also to provide a user-oriented system that ensures essential data for the construction site management while employing the standard software used in everyday engineering practice. The system is based mainly on smartphones, a common tool used in various industries. The system also doesn't need an extensive budget because using QR codes is a standard, low-cost technology generated in a closed dataset system (i.e., spreadsheet). In addition to smartphones, the system requires a personal computer, a tool that nowadays every engineer possesses.

Furthermore, using smartphones and personal computers ensures the system is portable and accessible to users on the construction site and in the office. This flexibility allows for real-time updates and communication, which can improve project coordination and decision-making. The system will undergo additional testing in laboratory assembly environment and on the construction site. In the further development the system's performance has to be tested for several stochastic difficulties common at construction sites, i.e., logistical problems, environmental concerns, and safety considerations. Additionally, evaluating the system in controlled laboratory assembly environments will allow assessing its correctness and dependability. The test results will improve the system, and any issues identified will be resolved, resulting in a more reliable and efficient system that can be applied on a greater scale.

The system's key drawbacks are the necessity for the stable and continuous internet access, ensuring the urgency and accuracy required for QR code scanning, continuous recording and monitoring on the construction site. Despite the system's relative independence, it is nonetheless advised that the construction site manager conducts an assessment and confirms the accuracy of the assembly. This is since the quality and comprehensiveness of the data collected are crucial to the system's efficiency. Therefore, it is necessary to ensure that all information is entered correctly and promptly into the system to avoid delays and potential errors in the project schedule. Despite the potential drawbacks, the development and implementation of the system can lead to more efficient construction practices. Furthermore, this research can serve as a starting point for further exploration of the potential applications of QR codes in the construction industry.

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References

[1] W. S. Alaloul, A. H. Qureshi, M. A. Musarat, and S. Saad, “Evolution of close-range detection and data acquisition technologies towards automation in construction progress monitoring,” Journal of Building Engineering, vol. 43, p. 102877, Nov. 2021, doi: 10.1016/j.jobe.2021.102877.

[2] B. Ekanayake, J. K.-W. Wong, A. A. F. Fini, and P. Smith, “Computer vision-based interior construction progress monitoring: A literature review and future research directions,” Automation in Construction, vol. 127, p. 103705, Jul. 2021, doi: 10.1016/j.autcon.2021.103705.

[3] M. Sami Ur Rehman, M. T. Shafiq, and F. Ullah, “Automated Computer Vision-Based Construction Progress Monitoring: A Systematic Review,” Buildings, vol. 12, no. 7, p. 1037, Jul. 2022, doi: 10.3390/buildings12071037.

[4] Z. Wang et al., “Vision-Based Framework for Automatic Progress Monitoring of Precast Walls by Using Surveillance Videos during the Construction Phase,” Journal of Computing in Civil Engineering, vol. 35, no. 1, Jan. 2021, doi: 10.1061/(asce)cp.1943-5487.0000933.

[5] X. Yan, H. Zhang, and W. Zhang, “Intelligent monitoring and evaluation for the prefabricated construction schedule,” Computer-Aided Civil and Infrastructure Engineering, vol. 38, no. 3, pp. 391–407, Mar. 2022, doi: 10.1111/mice.12838.

[6] W. van Groesen and P. Pauwels, “Tracking prefabricated assets and compliance using quick response (QR) codes, blockchain and smart contract technology,” Automation in Construction, vol. 141, p. 104420, Sep. 2022, doi: 10.1016/j.autcon.2022.104420.

[7] J. Abeid and D. Arditi, “Photo-net: an integrated system for controlling construction progress,” Engineering, Construction and Architectural Management, vol. 10, no. 3, pp. 162–171, Jun. 2003, doi: 10.1108/09699980310478412.

[8] N. Dawood, A. Akinsola, and B. Hobbs, “Development of automated communication of system for managing site information using internet technology,” Automation in Construction, vol. 11, no. 5, pp. 557–572, Aug. 2002, doi: 10.1016/s0926-5805(01)00066-8.

[9] J. Abeid, E. Allouche, D. Arditi, and M. Hayman, “PHOTO-NET II: a computer-based monitoring system applied to project management,” Automation in Construction, vol. 12, no. 5, pp. 603–616, Sep. 2003, doi: 10.1016/s0926-5805(03)00042-6.
[10] L. Jiao et al., “A Survey of Deep Learning-Based Object Detection,” IEEE Access, vol. 7, pp. 128837–128868, 2019, doi: 10.1109/access.2019.2939201.
[11] W.-S. Jang and M. J. Skibniewski, “A WIRELESS NETWORK SYSTEM FOR AUTOMATED TRACKING OF CONSTRUCTION MATERIALS ON PROJECT SITES,” JOURNAL OF CIVIL ENGINEERING AND MANAGEMENT, vol. 14, no. 1, pp. 11–19, Mar. 2008, doi: 10.3846/1392-3730.2008.14.11-19.
[12] C. Tang, Y. Ling, X. Yang, W. Jin, and C. Zheng, “Multi-View Object Detection Based on Deep Learning,” Applied Sciences, vol. 8, no. 9, p. 1423, Aug. 2018, doi: 10.3390/app8091423.
[13] C. Kim, B. Kim, and H. Kim, “4D CAD model updating using image processing-based construction progress monitoring,” Automation in Construction, vol. 35, pp. 44–52, Nov. 2013, doi: 10.1016/j.autcon.2013.03.005.
[14] Z. Pučko, N. Šuman, and D. Rebolj, “Automated continuous construction progress monitoring using multiple workplace real time 3D scans,” Advanced Engineering Informatics, vol. 38, pp. 27–40, Oct. 2018, doi: 10.1016/j.aei.2018.06.001.
[15] Q. Fang et al., “A deep learning-based method for detecting non-certified work on construction sites,” Advanced Engineering Informatics, vol. 35, pp. 56–68, Jan. 2018, doi: 10.1016/j.aei.2018.01.001.
[16] J. Wu, N. Cai, W. Chen, H. Wang, and G. Wang, “Automatic detection of hardhats worn by construction personnel: A deep learning approach and benchmark dataset,” Automation in Construction, vol. 106, p. 102894, Oct. 2019, doi: 10.1016/j.autcon.2019.102894.
[17] C. Kielhauser, R. Renteria Manzano, J. J. Hoffman, and B. T. Adey, “Automated Construction Progress and Quality Monitoring for Commercial Buildings with Unmanned Aerial Systems: An Application Study from Switzerland,” Infrastructures, vol. 5, no. 11, p. 98, Nov. 2020, doi: 10.3390/infrastructures5110098.
[18] A. Lanko, N. Vatin, and A. Kaklauskas, “Application of RFID combined with blockchain technology in logistics of construction materials,” MATEC Web of Conferences, vol. 170, p. 03032, 2018, doi: 10.1051/matecconf/201817003032.
[19] H. Zhang, X. Yan, H. Li, R. Jin, and H. Fu, “Real-Time Alarming, Monitoring, and Locating for Non-Hard-Hat Use in Construction,” Journal of Construction Engineering and Management, vol. 145, no. 3, Mar. 2019, doi: 10.1061/(asce)co.1943-7862.0001629.
[20] Microsoft "Power Apps" https://powerapps.microsoft.com/en-au/ accessed (Access date: 15.1.2023)

Disadvantages of EVM-type project management indicators

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Abstract

Tracking and monitoring become particularly important during the implementation phase of projects; however, participants should maintain some form of tracking and monitoring at all stages. It has taken decades for the use of milestones to be accompanied by sophisticated methods, even those required by law. Earned Value Management (EVM) is a managerial method used to control projects in terms of cost, time, and progress. Although many researchers have studied the EVM concept, only a few have attempted to suggest EVM frameworks for concurrent analysis of additional elements beyond time, cost, and progress. The importance of EVM is indicated by the fact that it is now a permanent chapter in methodologies and standards. In the meantime, several studies have shown EVM's shortcomings, and a number of researchers have proposed possible solutions (e.g., Earned Schedule or Earned Duration). This conference paper will summarize the most critical and recent additions, and based on them, further extension possibilities can be suggested.

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Keywords: earned value management, performance measurement, project control, project performance, tracking and monitoring.

1. Introduction

Earned value management (EVM) is a managerial method used to control projects in terms of cost, time, and progress. EVM is used as a guide for decision-making during the course of a project. It can be used as an alert system that lets management know when they need to take action in order to keep the project on track. This can help reduce problems before they become major issues, which will ultimately save money and time. Many different ways earned value management can be used. It can be used to monitor and control budgets, schedules, resource requirements, quality controls, and much more.

EVM can also be used as a predictive tool. This means that it can be used to predict when certain tasks will be completed, how much money they will cost, and how many resources will be needed. This can help managers plan ahead for upcoming events to ensure that everything goes as planned. Although many researchers have studied the EVM concept, only a few have attempted to suggest EVM frameworks for concurrent analysis of cost, quality, schedule, and risk. The Project Management Book of Knowledge (PMBoK) describes EVM as an approach that incorporates schedule, costs, and scope to assess and measure project performance [1]. Moreover, ISO 21508:2018 specifies earned value management principles for project and program management. It applies to any kind of organization, public or private, in any size or sector, as well as any type of project or program, regardless of complexity, size, or duration. However, it does not provide guidance on the use of specific processes, methods, or tools in the practice of earned value management, focusing instead on terms and definitions, benefits of an EVMS, an overview of the types of processes used, and the basic requirements of an EVMS [2].

2. Earned value management shortcomings

Nowadays, EVM is widely acknowledged as the most frequently used and approved project cost control system. Despite this widespread acceptance of EVM, a significant percentage of projects fail to meet baseline time and cost goals [3]. While numerous factors can contribute to project failure, a lack of attention to duration planning and control, as well as the reliability of estimations used in planning/scheduling etc. Although EVM was designed to monitor both time and cost, most research has focused on the cost factor. However, earned value management includes two well-known schedule performance indices to monitor project progress: schedule variance (SV) and schedule performance index (SPI) [4].

The SV compares the amount of work actually completed (i.e., earned) to the amount of work planned. However, the SV does not measure time but is presented in monetary units. If SV is less than zero, less work has been completed as planned, and the project is behind schedule. If SV is greater than zero, more work has been completed as planned, and the project is ahead of schedule. If SV=0, the completed work is as planned. The SPI is a dimensionless indicator used to measure work efficiency. It is the ratio of earned value to planned value, i.e., SPI=EV/PV. If SPI is less than 1 (=1, >1), the scheduling efficiency is less than (equal to, greater than) planned. At the completion of a project, the SPI is always equal to 1. On the other hand, whenever CV<0 and CPI=1, the project has over-costs (otherwise, if CV=0 and CPI=1, the project is under budget).

2.1. SV and SPI

Many authors have criticized the interpretation and behavior of the earned value management performance indicators SV and SPI over time. First, the SV is measured in monetary units rather than time units, which makes it harder to understand and, as a result, it is frequently misinterpreted. Second, an SV=0 (or SPI=1) might indicate that the work has been completed, but it could also indicate that it is running as planned. Finally, at the end of the project, the SV always converges to zero, signifying great performance even if the project is overdue. Likewise, even if the project is overdue, the SPI always converges to one at the completion, indicating 100% schedule efficiency. The SV and SPI thus lose their predictive power at a specific point in time, which is known as the “grey time area,” and often happens during the last third of the project [5].

As a matter of fact, this is generally the most critical stage where the predictions must be accurate, because top management needs to know when they can move on to the next project stage. Therefore, Lipke [5] proposed the concept of earned schedule (ES) to address the deficiencies with the earned value schedule performance indicators. This approach involves tracing the earned value forward or backward to the performance baseline (S-curve) or PV at a certain time point. It converts the EV into time increments and compares the actual project performance to the planned time performance. An $SV_{(t)}$=0 (>0) represents the number of time units by which the project lags (ahead) of its planned performance. The behaviour of $SV_{(t)}$ over time results in a final $SV_{(t)}$ that equals exactly the actual time difference at completion, while the SV always ends at zero. Moreover, the $SPI_{(t)}$ indicator has a final value representing project schedule performance while the SPI always equals 1 [5].

2.2. Project risk analysis

The EVM framework includes variances and performance indicators to notify project managers whether the project is overrun in costs or delays, but they do not notice whether the overruns are within the project’s expected range of variability. Due to the fact that EVM does not consider project risk analysis and variability, Javier Pajares, and Adolfo López-Paredes [6] developed two new metrics for integrating EVM with project risk management methodologies: Cost Control Index (CCoI) and Schedule Control Index (SCoI). These indexes compare EVM metrics with the maximum values the project should have if it ran under the risk analysis hypothesis [6]. So these two new metrics integrate EVM with project risk management methodologies, as EVM does not consider project risk analysis and variability.

2.3. *Forecasting accuracy*

Some researchers have proposed extensions to the basic procedures, mainly related to forecasting improvement. Vandevoorde and Vanhoucke [7], [8] summarise some of the cost and schedule forecasting methods and study their accuracy in real and simulated projects. In their comparative research of schedule performance metrics, they concluded that $SPI_{(t)}$ is a better indicator of project schedule performance than all other measures, including the traditional Schedule Performance Index [7], [8]. Lipke et al. [9] did a similar study, comparing the accuracy and reliability of a variety of indicators that may be used to predict the duration of a project at various stages of completion, presumably based on prior performance. They stated that SPI provides reasonably good forecasts only for big projects where the duration of the project is long, and the number of data used in the forecasting process is huge, whilst $SPI_{(t)}$ performs better in general. Whereas $SPI_{(t)}$ is suggested to be a better alternative for measuring duration/time performance than SPI, it has certain conceptual shortcomings and cannot be validated as a generic approach that applies to all cases [9]. The fundamental disadvantage of $SPI_{(t)}$ is that the same as SPI, it measures schedule performance in monetary terms of Earned Value (EV) and Planned Value (PV). In other words, the earned schedule method uses EV as a proxy to calculate the equivalent duration. ES, like any technique which uses EVM's cost-based measurements, is inherently insufficient for measuring duration performance. By using such models, the greater the disparity between a project's time and cost profiles, the more inaccurate the schedule performance offered. In such cases, $SPI_{(t)}$ and SPI will both produce inaccurate results, and $SPI_{(t)}$ may even perform worse than SPI [10].

EVM was designed primarily to focus on the large picture, i.e., total duration and cost at each stage. In other words, the project status is displayed as green as long as the total planned and actual cost and time metrics match. This method ignores the dynamics of event occurrence inside the system and has been disputed by other practitioners and researchers as well. To increase the accuracy of duration-focused performance assessment in EVM, Khamooshi and Golafshani [10] added earned duration while keeping the unique interplay of the three key project management variables of scope, cost, and time. The Total Planned Duration, Total Earned Duration, and Total Actual Duration graph (called EDM graph) is a highly strong tool focused on the duration that may serve the same purpose that the EVM graph does for cost. The newly proposed Project Progress Index (PPI), Duration Performance Index (DPI), and Earned Duration Index (EDI) are more effective duration-based performance indicators for project control and management. These metrics solve the shortcomings of cost-based schedule performance indexes [10]. Moreover, Byung-cheol and Reinschmidt [11] have proposed a new probabilistic forecasting method based on Bayesian inference and the Beta distribution, which integrates original estimates with observations of new actual performance. Furthermore, under this methodology, new real data generated during project run time is used to describe trends for the future project total cost and finishing date based on past performance [12].

2.4. *Quality*

Quality, as the third angle of the iron triangle, should be considered and controlled in the same way as schedule and cost to complete the goals of projects [13]. It is a challenge for many researchers and practitioners to suggest a framework to apply EVM to monitor and control the cost, quality, schedule, and risk of projects efficiently and effectively.

Khesal et al. [13] represented a new EVM framework by considering a quality control index. Particularly, some control indices and cumulative buffers are defined by two proposed methods, namely the linear- and Taguchi-based methods. The first proposed technique calculates Quality Actual Cost (QAC), which is the actual quality cost of work performed, based on a linear relationship with Quality Earned Value (QEV) which is the budgeted quality cost of work performed. Quality, according to Taguchi, is defined as the loss inflicted on society. As a result, the level of desirability is determined by the amount of loss. Furthermore, reduced quality loss leads to increased product desirability. Taguchi relates this loss to any variation in quality characteristics around its optimal point. This loss may involve dissatisfaction, inconvenience, financial and physical damage. The Taguchi technique is more strong in its approach to the cost of quality. The Taguchi loss function plays an important role in achieving Quality Actual Cost (QAC); thus, the Taguchi loss function is considered the loss function of quality cost in projects. The major output of this study is the control indices of cost, schedule, and quality. Therefore, new metrics and indices are prepared to compare cost, schedule, and quality variances with a maximum control deviation per time unit. Three new control indices, namely, Cost Control Index (CCoI), Schedule Control Index (SCoI), and Quality Control Index (QCoI), are defined to integrate EVM with quality and risk management.

Gao, X.K. and Ye, Z.M. [14] improved the model, which is based on the traditional EV model, quoting the definition of quality cost and combining the cost, progress, and quality, then forming the quality earned value system and coordinate coefficient of quality and progress. The coordinating coefficient index gives a new method for analyzing the scheduling condition and quality performance. The quality cost, an integral part of the total cost, can be decomposed into quality prevention, appraisal, and quality loss costs [14].

Moreover, Miguel, Madria, and Polancos [15] addressed the shortcomings and restrictions of the conventional EVM and suggested a new project management framework by integrating earned schedule, quality management, and risk management into earned value management. Using quality performance measures, their proposed model demonstrated how the quality issue affects a project's cost and schedule risk. Their model effectively uncovered hidden expenses such as rework and risk costs and integrated them into project and performance management, providing managers with better visibility. The standard EVM, on the other hand, is incapable of showing hidden costs and thus understates the project's progress. They introduced the quality performance indicators, which measure the ability of the project to deliver quality requirements throughout the project execution by calculating firstly the quality requirements (QR), which are the specifications set for the output of each milestone of the project. Secondly, the quality index number (QIN) is only the average of the QR rating for a certain milestone output. It indicates how much of the QR is met. If QIN < 1 indicates it did not meet its respective quality requirements. Thirdly, the quality earned value (QEV) is the portion of the earned value that passes the quality requirements. Finally, the quality performance index (QPI) this performance index indicates the efficiency of the project in meeting the quality requirements [15].

3. Conclusion

Earned value management is a project management approach used to control projects in terms of cost, time, and progress. EVM can help reduce problems before they become significant issues, save money and time, and can be used as a predictive tool to plan. EVM incorporates schedule, costs, and scope to assess and measure project performance, according to the Project Management Book of Knowledge and ISO 21508:2018. However, a significant percentage of projects fail to meet baseline time and cost goals despite the widespread acceptance of EVM. Most research on EVM has focused on cost rather than schedule performance. While EVM includes two schedule performance indices (SV and SPI), they lose their predictive power in the last third of the project, which is the most critical stage. Earned Schedule is a concept proposed by Lipke to address the deficiencies of EVM. ES compares actual project performance to planned time performance and traces earned value forward or backward to the performance baseline or planned value at a certain time point. ES converts the earned value into time increments and can accurately predict the time difference at completion. EVM also does not account for project risk analysis, including whether overruns are within a project's expected range of variability. To address this, researchers have proposed integrating risk analysis into the EVM framework to increase the accuracy of project cost and schedule forecasts. One of the primary goals of the earned value methods is to discover obstacles in execution instantaneously so that decisions may be made at the appropriate and required time. Similar to any approach, the value acquired has advantages and drawbacks; nevertheless, to get the desired outcomes in its application, it is necessary to be familiar with the application system. When appropriately used, the value earned is an essential tool for any project manager, assisting them in completing any project while fulfilling the basic criteria of time, cost, and scope.

References

[1] Project Management Institute and Project Management Institute, *A guide to the project management body of knowledge (PMBOK guide)*, 6th ed. Pennsylvania, USA: Project Management Institute, Inc, 2017.

[2] ISO, *ISO 21508:2018 - Earned value management in project and programme management*. 2018.

[3] GAO, *GAO cost estimating and assessment guide*. 2009.

[4] S. Vandevoorde and M. Vanhoucke, “A comparison of different project duration forecasting methods using earned value metrics,” *Int. J. Proj. Manag.*, vol. 24, no. 4, pp. 289–302, 2006, doi: 10.1016/j.ijproman.2005.10.004.

[5] W. Lipke, “‘Schedule is Different’ The Measurable News,” 2003.

[6] J. Pajares and A. López-Paredes, “An extension of the EVM analysis for project monitoring: The Cost Control Index and the Schedule Control Index,” *Int. J. Proj. Manag.*, vol. 29, no. 5, pp. 615–621, 2011, doi: 10.1016/j.ijproman.2010.04.005.

[7] S. Vandevoorde and M. Vanhoucke, “A comparison of different project duration forecasting methods using earned value metrics,” *Int. J. Proj. Manag.*, vol. 24, no. 4, pp. 289–302, May 2006, doi: 10.1016/J.IJPROMAN.2005.10.004.

[8] M. Vanhoucke and S. VANDEVOORDE, “A simulation and evaluation of earned value metrics to forecast the project duration,” *J. Oper. Res. Soc.*, vol. 58, no. 10, pp. 1361–1374, 2007.

[9] W. Lipke, O. Zwikael, K. Henderson, and F. Anbari, “Prediction of project outcome. The application of statistical methods to earned value management and earned schedule performance indexes,” *Int. J. Proj. Manag.*, vol. 27, no. 4, pp. 400–407, 2009, doi: 10.1016/j.ijproman.2008.02.009.

[10] H. Khamooshi and H. Golafshani, “EDM: Earned Duration Management, a new approach to schedule performance management and measurement,” *Int. J. Proj. Manag.*, vol. 32, no. 6, pp. 1019–1041, 2014, doi: 10.1016/j.ijproman.2013.11.002.

[11] B. Kim and K. F. Reinschmidt, “Probabilistic Forecasting of Project Duration Using Bayesian Inference and the Beta Distribution,” *J. Constr. Eng. Manag.*, vol. 135, no. 3, pp. 178–186, Mar. 2009, doi: 10.1061/(ASCE)0733-9364(2009)135:3(178).

[12] B. Kim and K. F. Reinschmidt, “Probabilistic Forecasting of Project Duration Using Bayesian Inference and the Beta Distribution,” *J. Constr. Eng. Manag.*, vol. 135, no. 3, pp. 178–186, 2009, doi: 10.1061/(asce)0733-9364(2009)135:3(178).

[13] T. Khesal, A. Saghaei, M. Khalilzadeh, M. Rahiminezhad Galankashi, and R. Soltani, “Integrated cost, quality, risk and schedule control through earned value management (EVM),” *J. Eng. Des. Technol.*, vol. 17, no. 1, pp. 183–203, 2019, doi: 10.1108/JEDT-07-2018-0119.

[14] X. Gao and Z. Ye, “The application of improved earned value model in engineering quality and progress coordination management,” *Appl. Mech. Mater.*, vol. 71–78, pp. 4580–4584, 2011, doi: 10.4028/www.scientific.net/AMM.71-78.4580.

[15] A. Miguel, W. Madria, and R. Polancos, “Project Management Model: Integrating Earned Schedule, Quality, and Risk in Earned Value Management,” *2019 IEEE 6th Int. Conf. Ind. Eng. Appl. ICIEA 2019*, pp. 622–628, 2019, doi: 10.1109/IEA.2019.8714979.

PRODUCTIVITY IMPROVEMENT AND DEVELOPING FRAMEWORK FOR ROADS MAINTENANCE: A CASE STUDY OF JOHANNESBURG ROADS AGENCY AND ETHEKWINI METROPOLITAN MUNICIPALITY

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Abstract

Municipalities in South Africa (SA) are battling to maintain their roads infrastructure utilising internal maintenance teams. The greatest concern among municipal staff seems to be a perceived lack of long-term performance and maintenance data (R. Lukes & C. Kloss, 2008). Several municipalities are struggling to operate and maintain their infrastructure in a cost-effective manner (IMESA, 2012). These municipalities are not providing enough maintenance budget for operations and maintenance which leads to poor infrastructure maintenance and resulting into ever ending infrastructure backlogs. There is a long turnaround time in attending to service requests in these municipalities and this might lead to potential accidents when repair work takes longer. There is also lack of efficiency and effectiveness to improving productivity by municipal maintenance internal teams

The developed framework standards for operation and maintenance of roads infrastructure for municipal teams will reduce turnaround time in attending to service requests, improve productivity and assist government allocation of resources per maintenance work activity. This will lead to systematic way of attending to maintenance work ensuring over 80% utilization of resources (plant, labour and material) and reduced wastage and idling time.

Keywords: capacity improvement, productivity improvement, roads maintenance framework, roads maintenance standards.

1. Introduction

There are eight metropolitan municipalities in South Africa (SA), namely: The City of Johannesburg Municipality, the City of Tshwane Municipality, the City of Ethekwini Municipality, the Buffalo City Municipality, the Mangaung Municipality, the City of Cape Town Municipality, Nelson Mandela Bay Municipality and the City of Ekurhuleni Municipality. The population that resides in these metropolitan municipalities is estimated at 33,7% of the entire SA population (Stats SA, 2016). These municipalities are at the centre of how South African citizens experience government services delivery. Governance is facilitated by a number of key infrastructures, the one being the road infrastructure network. This road network is the key enabling infrastructure where citizens move from one point to the next utilising different modes of transport. Part of the municipality's core mandate relating to road infrastructure is planning, designing and improving the system of movement in the city's streets, sidewalks and road intersections, including the traffic signal control system, to ensure safety and efficiency.

There is a need to direct limited resources from municipalities to address the most critical needs thereby achieving a balance between maintaining and renewing existing infrastructure whilst also addressing infrastructure backlogs (DPLG, 2006). The adequate maintenance of road infrastructure in municipalities is crucial, as maintenance prolongs the lifespan and delays reconstruction. Adequate maintenance will also allow government to spend a significate less amount as opposed to 100% on infrastructure reconstruction if there is no maintenance on a projects with a design life of ten years, this means in year seven the road will require total reconstruction (R. McCutcheon, 1989). When performance is not reported and measured, that will make it difficult to measure efficiency of the road maintenance teams in municipalities.

The City of Johannesburg (CoJ) roads are managed by the Johannesburg Roads Agency (JRA). The other seven out of the eight metros do not have agencies managing their road infrastructure, but rather a roads unit are part of the internal metro structure. The other seven metros' performance results and key performance indicators (KPis) are different from the JRA. In order to measure operational improvement and efficiency of the maintenance teams, the performance targets should be in terms of response time. The analysis of the metros' roads infrastructure performance targets indicates that the Johannesburg Metro is the only one that measures response time. However, asset management systems information is not often efficiently used in decisional process in most municipalities, which results in much waste in infrastructure maintenance time and effort (D. Michele & L Daniela, 2010).

Even though the JRA seems to measure performance better than other metros, there is no evidence of a scientific study performed by JRA or CoJ in generating KPis. The monitoring of services in municipalities requires the achievement of realistic goals (D. Prestorius & W. Schurink, 2007). There is also no evidence of a study done around the capacity of the JRA operational teams in responding to service requests prescribed in the JRA Service Level Agreement.

2. Methodology

The method to be utilized in the research is the qualitative one with a number of interview, on-site motion study and
checklists. To ensure validity and reliability, a structured questionnaire will be utilized for the participants to answer.
The on-site study will be done in order to record activities "as is", this motion study will also ensure reliability of information. The questionnaire will include some of the following questions:

- Are there specific teams for reactive and proactive maintenance?
- How many teams are responsible for proactive maintenance of potholes?
- How many teams are responsible for reactive maintenance of potholes?
- Are all the teams trained to repair potholes?
- Are all the required resources available for pothole repairs?
- How many service requests are received daily?
- How many service requests are related to pothole?
- Is there a system that records all service requests?
- What other means are utilized to record service requests?
- How many service requests are attended daily?
- How many repeat service requests related to potholes?
- How many pothole repairs are attended daily?
- How many pothole repairs completed daily?
- Was feedback provided to all reported service requests?

The data that will be collected in the motion study will include:

- Arrival of teams at workplace
- Any toolbox talks before leaving workplace for site
- Time teams leave workplace for site
- Arrival on site
- Number of teams per task
- Extent of task
- Commencement and completion of the task
- Resourced utilised to complete a task

The following personnel will be interviewed:

- Municipal management (Head of Department, Depot Managers)
- Foremen
- Employees (Pothole repair workers)

The research will focus on JRA under CoJ and eThekwini metros. The two metros have seven (7) depots each and the plan is to focus on two (2) depots per metro as the activities are similar to the rest of the depots. The two depots that will be selected will be the ones with a higher rate of unattended service requests.

The following are some of the limitation of the study:

- Key personnel to be interviewed not available
- Data maybe be not available for assessment
- Municipalities may see the study as an intrusion of their space

3. Results and Discussion

The results from this study will address following:

3.1Maintenance planning and scheduling

Investigating the utilisation of municipal internal capacity versus external service providers will include maintenance planning and scheduling of work by internal teams. The JRA diagnostic review revealed that currently reactive maintenance disrupts scheduled maintenance operations. The study will therefore find the root cause of the challenge and further propose ways of balancing planned versus reactive maintenance in these metros. This will be done as follows:

- Investigating ways to enable certain teams to do reactive maintenance and others to do proactive maintenance.
- Investigating ways to implement an appropriate ratio of reactive versus proactive maintenance teams across the two metros.
- Analysing the metros existing routine maintenance plans and investigating ways of improving them taking into consideration the existing resources.
- The study will also investigate ways for the metros to determine a more effective method of allocating resources between maintenance teams.

3.2 Relationship between Fleet and Plant and maintenance depots

Investigating the utilisation of maintenance equipment and plants within the depots, studies have shown that some of the factors affecting the performance of the in-house maintenance teams include a shortage of spare parts for minor plants and equipment. In addition, plants sometimes have to wait for imported parts for yellow plants such as graders, resulting in a plant standing idle for a long period. In order to improve the working relationship between the Fleet and Plant depot and the maintenance depots, the study will investigate the following:

- A Fleet and Plant needs plan
- A Fleet and Plant efficiency mechanism for effective utilisation of plant and equipment by maintenance depots

3.3 Motion study

When investigating the response time in attending to road infrastructure maintenance service requests, there is no evidence of a scientific study performed by any of the metros in measuring the time taken in attending to service requests. There is also no evidence of the study done around the capacity of the operational teams in responding to service requests.
As part of the study, the following will be addressed:

- Identifying or measuring and documenting average time in attending to service requests to identify current performance levels per operation team.
- Developing individual or team performance targets for maintenance activities based on the improved work processes.
- Documenting the improved work processes for the various work activities and their related standard resource requirements.

- Developing maintenance framework for roads.
- Identifying on-the-job training requirements for foremen, supervisors and managers on the implementation of the improved work processes.

3.4 Training and development

Investigating the need for training and development of internal maintenance teams, studies revealed that maintenance activities associated with surfaced roads are more than those of gravel roads and these activities are more labour intensive. Irvin (1975) states that the number of general workers in the government has decreased due to poor management of the staff replacement and recruitment processes. In addition, management does not timeously request placements as people leave the organisations. There has been no training and development for new and existing employed staff in more than 5 years at JRA, which might be the cause of JRA not meeting its service delivery standards (GTAC, 2016). The study will focus on the following:

- Investigating the implementation of recruitment plan
- Recommending the necessary required training and development for all maintenance teams
- Investigating the need to have an in-house training and development centre

4. Conclusion

The research into the South African metros reveals that most of them are struggling to meet their service delivery targets relating to in-house maintenance due to e.g. (a) Underfunding for roads resurfacing and maintenance; (b) Inappropriate skills of some depot managers, (c) Longer time taken in attending to service requests; and (d) High vacancy rate.
The key focus will be on the basics of operations management such as planning routine maintenance activities, measuring the process and the areas affecting production, and analysing all the work components related to roads maintenance (e.g pothole repairs), which will lead to cost-effective maintenance implementation. The outcomes of this study should lead to recommending the increase in metro in-house employment, training and development of in-house personnel, reducing the outsourcing of maintenance services and operational improvement and efficiency of in-house teams.
Holzer and Seok-Hwan (2004) indicate that productivity is a function of many factors, including the following:

- Top management support
- Committed personnel at all levels
- A performance measurement system
- Employee training
- Reward structures
- Community involvement and feedback for the correction of budget-management decisions

Linna et al. (2010) also reiterate that a productive society is dependent upon a high-performing government. The intention is to ensure that improved productivity and efficiency in the road maintenance is supported by all parties involve, from the top management to the general workers.

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References

[1] "South Africa - Census, Standards & Statistics," Foreign Law Guide, doi: 10.1163/2213-2996_flg_com_322456.
[2] "Improving Office Productivity: A Guide for Business and Facilities Managers," Work Study, vol. 49, no. 3, Jun. 2000, doi: 10.1108/ws.2000.07949cae.003.

[3] D. S. Michele and L. Daniela, “Decision-support tools for municipal infrastructure maintenance management,” Procedia Computer Science, vol. 3, pp. 36–41, 2011, doi: 10.1016/j.procs.2010.12.007.
[4] D. Pretorius and W. Schurink, “Enhancing service delivery in local government: the case of a district municipality,” SA Journal of Human Resource Management, vol. 7, no. 1, pp. 19–29, Jul. 2007, doi: 10.4102/sajhrm.v5i3.148.
[5] N. K. Marutlulle, “Government contribution to housing delivery challenges in Ekurhuleni Metropolitan Municipality: An exploration,” Africa’s Public Service Delivery and Performance Review, vol. 7, no. 1, May 2019, doi: 10.4102/apsdpr.v7i1.215.
[6] F. Manqele, “Public participation in municipal service delivery in the eThekwini Municipality”, doi: 10.51415/10321/3898.
[7] M. A. Katouzian, “G. W. Irvin, Roads and Redistribution: Social Costs and Benefits of Labour-Intensive Road Construction in Iran (Geneva: International Labour Office, 1975). Pp. 162.,” International Journal of Middle East Studies, vol. 9, no. 3, pp. 422–423, Aug. 1978, doi: 10.1017/s002074380003381x.
[8] R. Stewart et al., “The effects of training, innovation and new technology on African smallholder farmers’ wealth and food security,” Jul. 2016, doi: 10.23846/sr1079.
[9] J. Mescht and M. Jaarsveld, “Figure 2.22. Local authority revenues are much smaller in poorer municipalities”, doi: 10.1787/888934153274.
[10] M. Colclough and M. E. Mundel, “Improving Productivity and Effectiveness,” The Journal of the Operational Research Society, vol. 34, no. 9, p. 917, Sep. 1983, doi: 10.2307/2580984.
[11] S. Hull, T. Sehume, S. Sibiya, L. Sothafile, and J. Whittal, “Land allocation, boundary demarcation and tenure security in tribal areas of South Africa,” South African Journal of Geomatics, vol. 5, no. 1, p. 68, Mar. 2016, doi: 10.4314/sajg.v5i1.5.
[12] T. Bovaird, “THE PUBLIC PRODUCTIVITY HANDBOOK - Edited by Marc Holzer and Seok-hwan Lee,” Public Administration, vol. 84, no. 4, pp. 1090–1093, Dec. 2006, doi: 10.1111/j.1467-9299.2006.00628_3.x.
[13] R. McCutcheon, “Labour-intensive road construction in Africa,” Habitat International, vol. 13, no. 4, pp. 109–123, Jan. 1989, doi: 10.1016/0197-3975(89)90042-8.
[14] P. Linna, S. Pekkola, J. Ukko, and H. Melkas, “Defining and measuring productivity in the public sector: managerial perceptions,” International Journal of Public Sector Management, vol. 23, no. 3, pp. 300–320, Apr. 2010, doi: 10.1108/09513551011032491.
[15] R. T. McCutcheon, “The main findings of the district pilot project of labour-intensive road construction and maintenance in Botswana and the implications for similar projects in South Africa,” Development Southern Africa, vol. 8, no. 2, pp. 149–170, May 1991, doi: 10.1080/03768359108439578.
[16] S. Phillips, P. Delius, and R. McCutcheon, “Planning labour-intensive employment creation programmes for the short term,” Development Southern Africa, vol. 12, no. 2, pp. 237–247, Apr. 1995, doi: 10.1080/03768359508439808.
[17] F. L. M. Taylor Parkins and R. T. McCutcheon, “Visualisation of construction costs and techniques of employment-intensive road construction in developing areas,” 1999 IEEE International Conference on Information Visualization (Cat. No. PR00210), doi: 10.1109/iv.1999.781563.

SCHEDULING REPETITIVE CONSTRUCTION PROCESSES USING A SWARM ALGORITHM

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Abstract
This article presents a method for multi-criteria optimization of repetitive construction processes schedules. Considering the limitations in planning the realization of such projects using classical tools and methods, the use of swarm algorithm for finding non-dominated solutions to the problem was proposed. An example of the application of the particle swarm optimization algorithm to the development of a schedule for the repetitive construction processes realization and the selection of work crews in order to minimize the realization time of the project and downtime in the work crews was also presented.

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Keywords: construction project management, construction scheduling, metaheuristic algorithm, particle swarm optimization, repetitive project scheduling.

1. Introduction

The realization of construction projects often includes the execution of a number of repetitive processes on the objects of a given construction project or their parts, referred to as working units. In literature, this type of projects are described as repetitive [1]–[3]. Due to the specific nature of the realization conditions, the classical planning methods (critical path method, PD method or PERT) are not adapted to support the management of this type of projects [4]–[6]. Therefore, a number of methods have been developed dedicated to the design of repetitive construction projects realization, such as LSM (Linear Scheduling Method) [7], RSM (Repetitive Scheduling Method) [8] or TACT and e-TACT methods [9]. One of the more popular approaches to support the management of repetitive construction projects when seeking multi-criteria optimization is mathematical modelling of construction management's preferences regarding optimization goals, taking into account the imposed realization constraints, and then solving the developed model using exact or heuristic (usually of high computational complexity), or meta-heuristic methods – in the case of complex scheduling problems occurring in practice. Meta-heuristic algorithms provide a general scheme for solving an optimization problem, based on processes occurring in nature, e.g. adaptation in the evolution process. An example of meta-heuristic algorithms, often used to solve scheduling problems, especially in industry, are swarm algorithms, for which an attempt was made in this paper to apply them to solve the problem under study.

2. Literature review

2.1. Meta-heuristic swarm algorithms

Optimization of schedules for repetitive construction projects is a difficult and complex process due to the following problems [10]–[12]:

- the number of possible solutions in the search area is so large that it makes it impossible or meaningless to use a comprehensive search to find the best solution,
- the model of the problem usually includes many constraints, which makes it difficult to generate even one acceptable solution, let alone find the optimal solution,

- the problem is so complex that in order to obtain a solution with a reasonable amount of computational time, it is necessary to use problem models so simplified that any solution is practically worthless,
- the value of the criterion function is affected by many decision variables, therefore it is necessary to review many solutions acceptable for various combinations of their values,
- the person solving the problem usually does not have the appropriate knowledge and skills in solving complex mathematical models.

Due to the aforementioned difficulties in finding solutions to the problem of scheduling repetitive construction projects, more and more perfect algorithms are constantly being sought to find an approximate, but still useful solution. One of the most popular approaches to finding suboptimal solutions to real problems is the use of meta-heuristics algorithms. Many of them are inspired by phenomena occurring in nature – the observation of behavior occurring in nature makes it possible to transfer existing phenomena to algorithmic procedures [13]. Among the numerous methods belonging to this group, the following can be mentioned:

- evolutionary algorithms, including genetic ones, based on the mechanisms of natural evolution,
- quantum genetic algorithms using the laws of quantum physics,
- artificial immune systems based on processes occurring in the immune system,
- artificial neural networks, imitating the processes in the human brain,
- simulated annealing algorithms resembling the annealing phenomenon known from metallurgy,
- herd algorithms, also called swarm algorithms, which derive from the so-called swarm intelligence of social organisms living in colonies.

Swarm algorithms have become increasingly popular in recent years. One of the reasons for this is their very large variety and the ability to adapt to the problem under consideration. Organism communities are a decentralized system composed of autonomous individuals, which can be described by certain probabilistic behavior – reactions to stimuli. The basic rules of their behavior are the result of local interactions and guarantee the spread of information within the colony and affect the attitudes of each individual. In herd behavior, coordination within a group of individuals corresponds with the organization of tasks required to solve a particular problem, while proper communication helps to make the best choice by exchanging information between individuals [13]. Table 1 summarizes the types of organisms and the type of herd behavior on which optimization in previously developed swarm algorithms is based.

The general scheme of the swarming algorithm can be written as follows [13]:

- coding and initialization of the initial population of solutions and evaluation of their quality,
- until the stopping criteria of the algorithm are met, cyclically repeat the following steps:
  - identification of the vicinity of current individuals,
  - selection of individuals representing the best solutions from the vicinity,
  - acceptance or rejection of candidate solutions,
  - creating a new population of solutions,
- decoding the best solutions found.

Table 1. Types of herd organisms on whose behavior swarming algorithms are based (based on [14])

.

Organism	Type of herd behaviour
ants	foraging
particles	aggregating
bees	foraging
masses	gathering
wolves	preying
bats	echolocation
bacteria	growth
fish	aggregating
birds	mating
dolphins	clustering
monkeys	climbing
fruit fly	gathering
firefly	gathering
cockroaches	foraging
cuckoos	brooding
krill	herding
frogs	jumping

2.2. Repetitive construction projects

In the unusually rich literature on the subject, one can find various tools tailored to optimize construction schedules of repetitive projects. The most frequently used methods of optimizing the schedules of repetitive projects include exact methods of solving mathematical models in the form of linear [15]–[16] or dynamic programs [17], as well as heuristic and meta-heuristic methods, e.g. genetic algorithms [18]–[19] and other more advanced ones [20]–[21]. Approaches using fuzzy logic are also being developed [22]. Some works have developed methods for determining construction schedules under risk conditions using simulation [23].

Regardless of the method of solution or modelling, the problem of scheduling repetitive projects was formulated with the following objectives in mind: minimizing the total project realization time [24]–[25], ensuring that the project deadline is met [26], minimizing the total cost of the project [27], seeking a compromise between the time and cost of the project [28], maximizing work efficiency [29], schedule resilience and reliability [30], ensuring the continuity of resources (minimizing downtime) [4], [16], minimizing the cost of breaks in the crews work [19] a combination of these criteria [5], [31]–[32].

For example, Sroka et al. [33] presented a model for scheduling repetitive construction projects in order to support the selection of the appropriate method of their realization and optimize the general contractor's profit, taking into account the amount of direct and indirect costs, as well as contractual penalties and the cost of downtime of work crews and credit service costs. The model was solved using a hybrid algorithm using a simulated annealing algorithm and a genetic algorithm. The operation of the proposed model was presented on a calculation example, and the results obtained in the model are fully satisfactory.

In turn, Tran, Chou and Luong [34] developed a stochastic model minimizing the realization time of a repetitive construction project, taking into account the different priorities of process significance. A new fuzzy hybrid evolutionary approach, called the artificial bee colony approach, was used to solve the developed model. Experimental results indicate that the proposed method provides the shortest average project realization time and the smallest standard deviation in relation to the optimal solution among the model algorithms considered in the work.

The same authors developed a method of finding compromise schedules due to the time and cost of realization. In [21] an adaptive multi-criteria search algorithm for symbiotic algorithms was developed. Two case studies were analyzed to validate the scheduling method, as well as to demonstrate the possibility of using the new algorithm to generate solutions. The obtained results indicate that the proposed algorithm is more effective in comparison with the basic search algorithm for symbiotic organisms and others analysed in this work.

The model developed by Wang et al. [35] makes it possible to search for a compromise between the time, cost and quality of repetitive construction projects. The authors used the NGSA (Non-Dominated Sorting Genetic Algorithm) to find non-dominated solutions to the developed problem model. An undoubted advantage of their approach is the quantitative consideration of the quality of the realized works.

The genetic algorithm was also used by Altuwaim and El-Rayes [19] to simultaneously minimize the duration of a repetitive construction project, the downtime of work crews and the cost of these interruptions. The algorithm for solving this problem includes four modules: optimisation, initial scheduling, intermediate scheduling and determining the cost of downtime for crews.

3. USING THE SWARM ALGORITHM FOR SCHEDULING REPETITIVE CONSTRUCTION PROCESSES – EXAMPLE

New methods of scheduling repetitive construction projects have been developed very dynamically in the last decade based on increasingly modern and advanced techniques. Nevertheless, it is very difficult to find in the literature examples of the use of swarm algorithms for scheduling the realization of repetitive construction projects. These algorithms are an extremely flexible and effective tool for finding suboptimal solutions to even very complex computational problems. Therefore, in this publication one of the swarm algorithms (particle swarm optimization algorithm) was used to determine the schedule of an exemplary construction project. The block diagram of this algorithm is shown in Figure 1.

The analyzed project consists of seven real processes and two fictitious ones: the beginning and the end of the project. The project includes the realization of three identical working buildings, being separate working units. The same processes are performed on each of them. Sequence relationships between processes within one working unit are shown in Figure 2. Two crews are available: crew B1 and crew B2. They can be assigned to realize different processes. The realization times of individual processes are shown in Figure 2 (the realization times of processes on individual work plots are the same). Due to the use of the learning effect, the crew assigned to realize a particular process will realize it on all work plots.

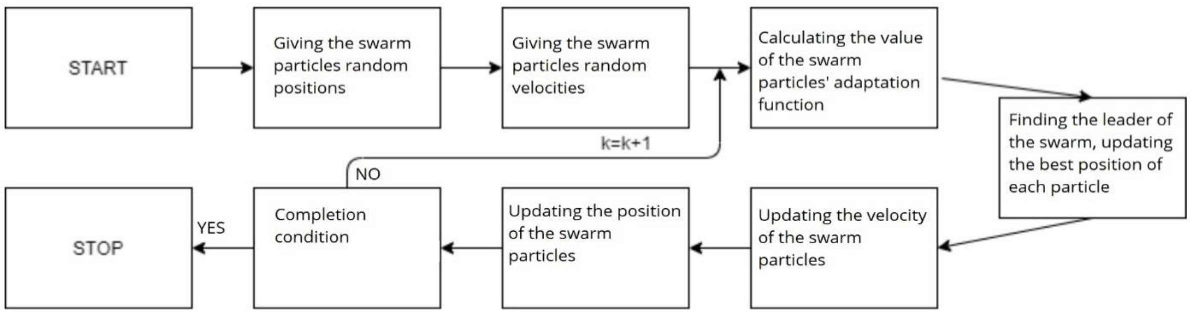

Fig. 1. Block diagram of the particle swarm optimization algorithm (based on [36])

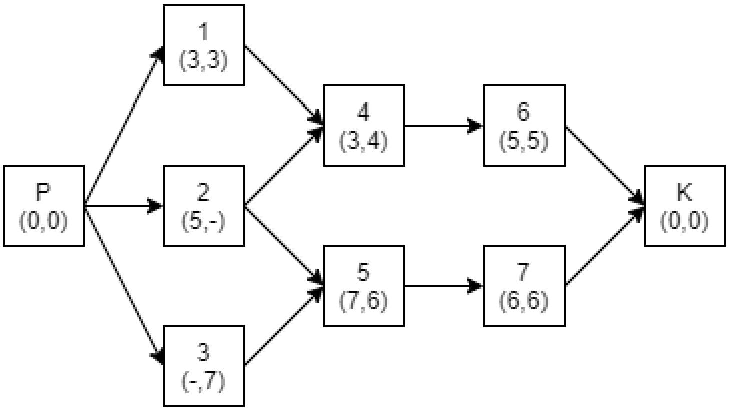

Fig. 2. Network model of processes realized on one working unit of an exemplary construction project (times of realization of individual project processes by crews B1 and B2, expressed in working days, are given in brackets)

As an example, the project realization schedule was simultaneously optimized in terms of three criteria:

- minimizing the realization time of the project
- minimizing the downtime of working crews,
- minimizing the realization time of construction facilities, remaining in relationship with the reduction of downtime on work fronts assuming that they are equivalent.

The example was solved using a particle swarm optimization algorithm. The calculation time was 46.53 seconds. The resulting schedule is shown in Figure 3 in the form of a beam graph. Crews B1 and B2 work without breaks, the realization time of the entire project was 57 working days, and the realization of each building object averaged 46 working days.

The developed algorithm can also be used for scheduling the realization of processes repeated on heterogeneous units, finding the optimal order of plot realization. Extensive examples of its use are presented in [37].

4. Summary

The article presents a method of scheduling repetitive construction projects using one of the swarm algorithms – the particle swarm optimization algorithm. The method presented in the article makes it possible to obtain compromise solutions due to three optimization criteria: minimizing the realization time of construction objects (work units) and the entire project, and minimizing the downtime of crews work. The obtained results indicate that the use of swarm algorithms for scheduling repetitive construction projects generates very good results and can support construction managers in finding solutions to this complex problem.

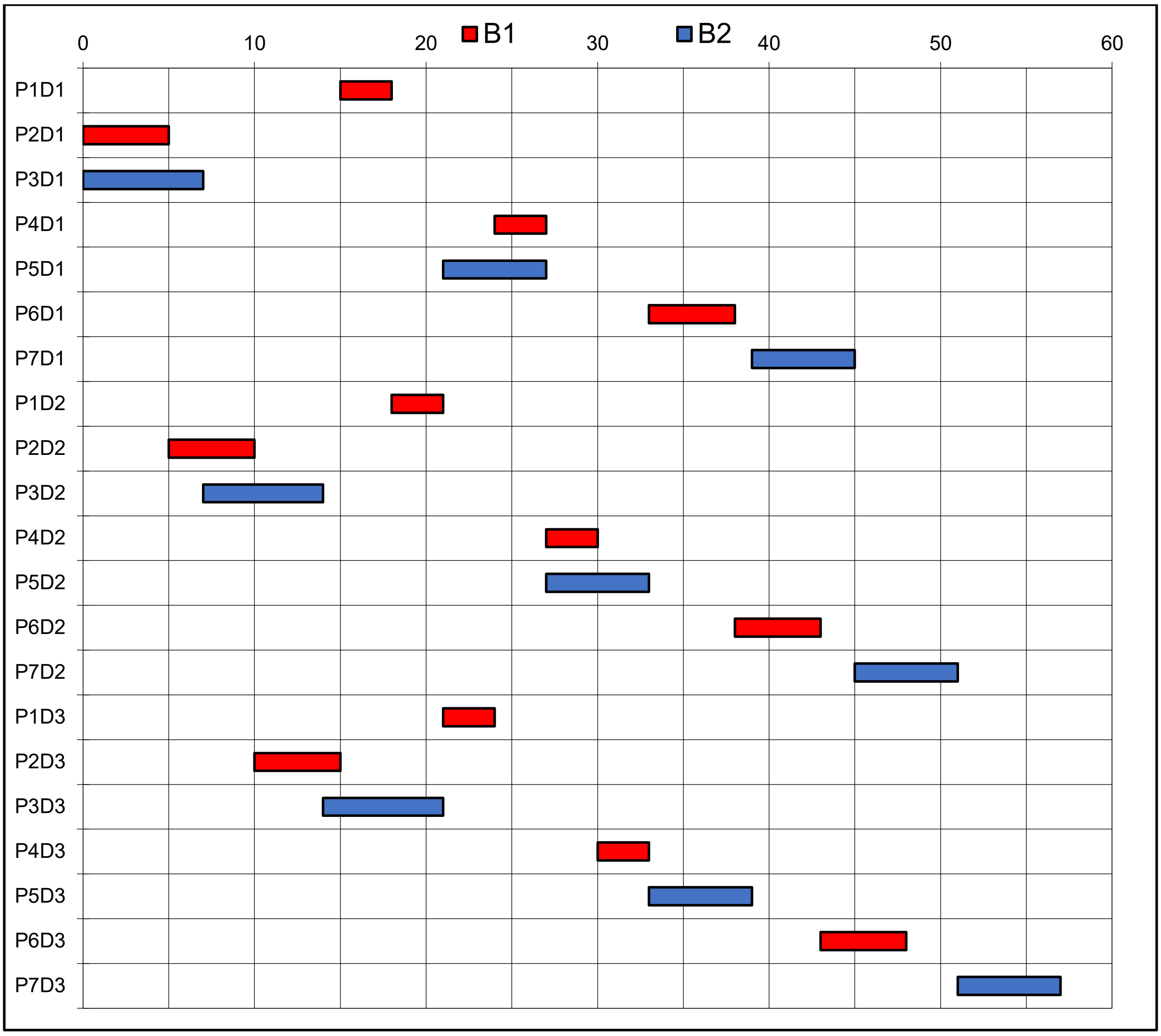

Fig. 3. Beam project realization schedule (solution for equal weights of optimization criteria)

Acknowledgements

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References

[1] M. Tomczak, P. Jaśkowski, „The method of scheduling construction projects increasing the use of resources of the general contractor," A. Juozapaitis, A. Daniūnas, L. Juknevičius (Eds.), The proceedings of the 13th international conference "Modern Building Materials, Structures and Techniques (MBMST 2019)", Vilnius Gediminas Technical University, 2019, pp. 683–690, 2019, doi: 10.3846/mbmst.2019.019.

[2] T. Hegazy, M. Abdel-Monem, D.A. Saad, „Framework for enhanced progress tracking and control of linear projects," Engineering, Construction and Architectural Management, vol. 21, no. 1, pp. 94–110, 2012, doi: 10.1108/ECAM-08-2012-0080.

[3] X. Zou, L. Zhang, „A constraint programming approach for scheduling repetitive projects with atypical activities considering soft logic," Automation in Construction, vol. 109, 102990, 2019 doi: 10.1016/j.autcon.2019.102990.

[4] M. Tomczak, P. Jaśkowski, „New approach to improve general contractor crew's work continuity in repetitive construction projects," Journal of Construction Engineering and Management, vol. 146, no. 5, 04020043, 2020, doi: 10.1061/(ASCE)CO.1943-7862.0001824.

[5] M. Tomczak, „Modeling of the harmonization method for executing a multi-unit construction project," Open Engineering, vol. 9, no. 1, pp. 282-291, 2019, doi: 10.1515/eng-2019-0036.

[6] Y. Su, G. Lucko, „Linear scheduling with multiple crews based on line-of-balance and productivity scheduling method with singularity functions," Automation in Construction, vol. 70, pp. 38-50, 2016, doi: 10.1016/j.autcon.2016.05.011.

[7] D.J. Harmelink, J.E. Rowings, „Linear scheduling model: Development of controlling activity path," Journal of Construction Engineering and Management, vol. 124, no. 4, pp.263–268, 1998, doi: 10.1061/(ASCE)0733-9364(1998)124:4(263).
[8] R.B. Harris, P.G. Ioannou, „Scheduling projects with repeating activities," Journal of Construction Engineering and Management, vol. 124, no. 4, pp.269–278, 1998, https://doi.org/10.1061/(ASCE)0733-9364(1998)124:4(269)
[9] D. Lee, D.-S. Kim, G.-H. Kim, S. Kim, „Time reduction effect of the enhanced TACT method for high-rise residential buildings," Journal of Civil Engineering and Management, vol. 22, no. 7, pp. 944-953, 2016, doi: 10.3846/13923730.2014.945949.
[10] Z. Michalewicz, D.B. Fogel, „Jak to rozwiązać czyli nowoczesna heurystyka (How to Solve It: Modern Heuristics)," Wydawnictwa Naukowo-Techniczne, Warszawa, 2006, ISBN: 83-204-3108-5.
[11] D.H. Tran, „Optimizing time–cost in generalized construction projects using multiple-objective social group optimization and multi-criteria decision-making methods," Engineering, Construction and Architectural Management, vol. 27, no. 9, pp. 2287-2313, 2020, doi: 10.1108/ECAM-08-2019-0412.
[12] I. Bakry, O. Moselhi, T. Zayed, „Optimized acceleration of repetitive construction projects," Automation in construction, vol. 39, pp. 145-151, 2014, doi: 10.1016/j.autcon.2013.07.003.
[13] J. Kwiecień, „Algorytmy stadne w rozwiązywaniu wybranych zagadnień optymalizacji dyskretnej i kombinatorycznej (Swarm algorithms in solving selected discrete and combinatorial optimization problems)," Wydawnictwa AGH, Kraków, 2015. ISSN 0867-6631.
[14] S. Zhang, C.K.M. Lee, H.K. Chan, K.L. Choy, Z. Wu, „Swarm intelligence applied in green Logistics: A literature review," Engineering Applications of Artificial Intelligence, vol. 27, pp. 154-169, 2015, doi: 10.1016/j.engappai.2014.09.007.
[15] P.G. Ipsilandis, „Multiobjective linear programming model for scheduling linear repetitive projects," Journal of Construction Engineering and Management, vol. 133, no. 6, pp. 417-424, 2007. doi: 10.1061/(ASCE)0733-9364(2007)133:6(417).
[16] P. Jaśkowski, M. Tomczak, „Problem minimalizacji przestojów w pracy brygad generalnego wykonawcy w harmonogramowaniu przedsięwzięć budowlanych (Minimisation of work gaps for general contractor crews in construction project scheduling)," Przegląd Naukowy. Inżynieria i Kształtowanie Środowiska, vol. 26, no. 2, pp. 193-201, 2017, doi: 10.22630/PNIKS.2017.26.2.17.
[17] I. Bakry, O. Moselhi, T. Zayed, „Optimized scheduling and buffering of repetitive construction projects under uncertainty," Engineering, Construction and Architectural Management, vol. 23, no. 6, pp. 782-800, 2016, doi: 10.1108/ECAM-05-2014-0069.
[18] Y. Huang, X. Zou, L. Zhang, „Genetic algorithm–based method for the deadline problem in repetitive construction projects considering soft logic," Journal of Management in Engineering, vol. 32, no. 4, 04016002, 2016, doi: 10.1061/(ASCE)ME.1943-5479.0000426.
[19] A. Altuwaim, K. El-Rayes, „Optimizing the Scheduling of Repetitive Construction to Minimize Interruption Cost," Journal of Construction Engineering and Management, vol. 144, no. 7, 04018051, 2018, doi: 10.1061/(ASCE)CO.1943-7862.0001510.
[20] G.A. Duffy, G.D. Oberlender, D.H. Seok Jeong, „Linear scheduling model with varying production rates," Journal of Construction Engineering and Management, vol. 137, no. 8, pp. 574-582, 2010, doi: 10.1061/(ASCE)CO.1943-7862.0000320.
[21] D.-H. Tran, J.-S. Chou, D.-L Luong, „Multi-objective symbiotic organisms optimization for making time-cost tradeoffs in repetitive project scheduling problem," Journal of Civil Engineering and Management, vol. 25, no. 4, pp. 322-339, 2019, doi: 10.3846/jcem.2019.9681.
[22] A. Maravas, J.P. Pantouvakis, „Fuzzy repetitive scheduling method for projects with repeating activities," Journal of Construction Engineering and Management, vol. 137, no. 7, pp.561-564, 2011. doi: 10.1061/(ASCE)CO.1943-7862.0000319.
[23] J. Yoon, I. Yu, „Estimating normal duration of renovation for multistory apartment building considering extension-type renovation projects," Journal of Civil Engineering and Management, vol. 25, no. 2, pp. 156-167, doi: 10.3846/jcem.2019.8024.
[24] E. Radziszewska-Zielina, B. Sroka. „Planning repetitive construction projects considering technological constraints," Open Engineering, vol. 8, no. 1, pp. 500-505, 2018, doi: 10.1515/eng-2018-0058.
[25] P. Jaśkowski, S. Biruk, „Minimizing the Duration of Repetitive Construction Processes with Work Continuity Constraints," Computation, vol. 7, no. 1, 14, doi: 10.3390/computation7010014.
[26] H.R.Z. Dolabi, A. Afshar, R. Abbasnia, „CPM/LOB scheduling method for project deadline constraint satisfaction," Automation in Construction, vol. 48, pp. 107-118, doi: 10.1016/j.autcon.2014.09.003.
[27] M. Podolski, B. Sroka, „Cost optimization of multiunit construction projects using linear programming and metaheuristic-based simulated annealing algorithm," Journal of Civil Engineering and Management, vol. 25, no. 8, pp. 848-857, 2019, doi: 10.3846/jcem.2019.11308.
[28] X. Zou, S.C. Fang, Y.S. Huang, L.H. Zhang, „Mixed-integer linear programming approach for scheduling repetitive projects with time-cost trade-off consideration," Journal of Computing in Civil Engineering, vol. 31, no. 3, 06016003, 2017, doi: 10.1061/(ASCE)CP.1943-5487.0000641.
[29] G. Lucko, T.D.C. Alves, V.L. Angelim, „Challenges and opportunities for productivity improvement studies in linear, repetitive, and location-based scheduling," Construction Management and Economics, vol. 32, no. 6, pp. 575-594, 2014, doi: 10.1080/01446193.2013.845305.
[30] F. Moreno, F. Orozco, O. Rojas, B. Senior, M. Poshdar, E. Forcael, „A Fixed Start Scheduling Approach for Repetitive Construction Projects," KSCE Journal of Civil Engineering, vol. 24, pp. 1671–1682, 2020, doi: 10.1007/s12205-020-1429-8.
[31] G. Lucko, L.G. Araújo, G.R. Cates, „Slip chart–inspired project schedule diagramming: origins, buffers, and extension to linear schedules," Journal of Construction Engineering and Management, vol. 142, no. 5, 04015101, 2016, doi: 10.1061/(ASCE)CO.1943-7862.0001089.
[32] M. Skibniewski, J. Moliński, „Modelling of building production activities for multifacility projects," Construction Management and Economics, vol. 7, no. 4, pp. 357-365, 1989, doi: 10.1080/01446198900000034.

[33] B. Sroka, J. Rosłon, M. Podolski, W. Bożejko, A. Burduk, M. Wodecki, „Profit optimization for multi-mode repetitive construction project with cash flows using metaheuristics," Archives of Civil and Mechanical Engineering vol. 21, no. 2, pp. 1-17, 2021, doi: 10.1007/s43452-021-00218-2.

[34] D.H. Tran, J.S. Chou, D.L. Luong, „Optimizing non-unit repetitive project resource and scheduling by evolutionary algorithms," Operational Research, vol. 22, no. 1, pp. 77-103, 2022, doi: 10.1007/s12351-019-00544-7.

[35] T. Wang., M. Abdallah, C. Clevenger, S. Monghasemi, „Time–cost–quality trade-off analysis for planning construction projects," Engineering, Construction and Architectural Management, vol. 28, no. 1, pp. 82-100, 2021, doi: 10.1108/ECAM-12-2017-0271.

[36] M. Szczepanik, „Algorytmy rojowe w optymalizacji układów mechanicznych (Swarm algorithms in optimization of mechanical systems)," Wydawnictwo Politechniki Śląskiej, Gliwice, 2013, ISBN 9788378801382.

[37] M. Tomczak, P. Jaśkowski, „Harmonizing construction processes in repetitive construction projects with multiple buildings," Automation in construction, vol. 139, 104266, 2022, doi: 10.1016/j.autcon.2022.104266.

STUDY ON SIMULATION TECHNOLOGY TO EVALUATE WORKING TIME FROM BIM DATA AND MESH DATA

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Abstract

Research on four-dimensional (4D) building information modeling (BIM) simulations has recently been actively conducted. However, the 4D BIM simulation often draws the installation order of the building parts. Therefore, only a few studies have analyzed the changes in working time owing to differences in the installation order of building parts. In this study, the effect of the difference in the installation order of the building parts on work time was investigated. After reproducing the construction site in the virtual space, an agent that shuttles between the stockyard and the installation location was created. This agent can move around and avoid newly installed members as construction progresses. Therefore, the total moving distance of the agent changes depending on the installation order of the building parts. Based on changes in the total moving distance, a method was devised for evaluating the goodness or badness of the installation order of building parts. Subsequently, the developed simulation system was applied to install studs on the partition walls. In addition, the simulation system was applied to new constructions and renovation works. When applying the system to renovation work, simulations were performed using mesh data created based on the point-cloud data of existing buildings.

Keywords: 4D simulation, building information modeling, installation order, worker movement routes.

1. Introduction

In Japan, building information modeling (BIM) data are widely used in construction work, particularly for clash detection between the structural frame and building equipment. Four-dimensional (4D) BIM simulations have also been extensively applied for construction visualization. Thus, the use of BIM data has become common in new constructions in Japan. However, several issues are associated with 4D BIM simulations, among which a method whereby a human considers and inputs the construction order is mainstream.

In recent years, 4D simulations have been extensively studied, and several studies have been conducted on the automatic creation of construction sequences. Many technological developments have been made in 4D simulations [1]–[3]. Some studies applied 4D simulations to safety measures [4], and numerous examples of applied research linking 4D simulations and virtual reality have been reported [5]. Many 4D simulations have reproduced the movements of cranes [6], [7] and have been applied in the production of unitized building parts [8]. The organization of BIM data in 4D simulations has also been investigated [9], [10]. In addition, studies and discussions regarding the introduction status and future of 4D simulations have been reported [11], [12].

In this study, considering the interior finishing work in building construction, a system that simulates the interior finishing work procedure was developed. In this simulation of interior construction, a mechanism was introduced, wherein the movement route of a worker changed depending on the order in which the walls were assembled. Considering this, the order of the detailed tasks was determined as good or bad. In addition, the number of new construction projects in Japan is expected to decrease, and that of renovation projects will increase. Therefore, we developed an application for simulating interior construction during renovation.

2. Method for predicting work time from BIM data

2.1. Processing procedure for predicting work time from BIM data

A system that predicts the work time for specific types of interior construction work was developed in this study. This system can automatically determine the route of a worker from the stockyard to the installation points of building components. In addition, by installing building members, a mechanism was introduced, which created spaces that workers were unable to pass through.

The developed system predicts work time according to the following calculation procedure:

(1) Entering the installation location of building components

(2) Determining the installation order of building components

(3) Calculating the movement route of the workers

(4) Aggregating the total distance traveled

This system was developed using Unity. BIM data was read in 3ds format, which creates the movement route of the worker and draws a 4D BIM simulation.

2.2. Entering the installation location of building components

Installation points were set up for building components such as studs to execute a 4D BIM simulation that installs the interior components.

Figure 1 shows the substrates of the two interior partition walls. The left side of Fig. 1 shows the complete shape of the interior partition walls. The right side of Fig. 1 shows the installation positions of the studs forming the base of each wall. Workers in the virtual space move from the stockyard to the installation point. After completing the installation, the worker returns to the stockyard to pick up the next building member.

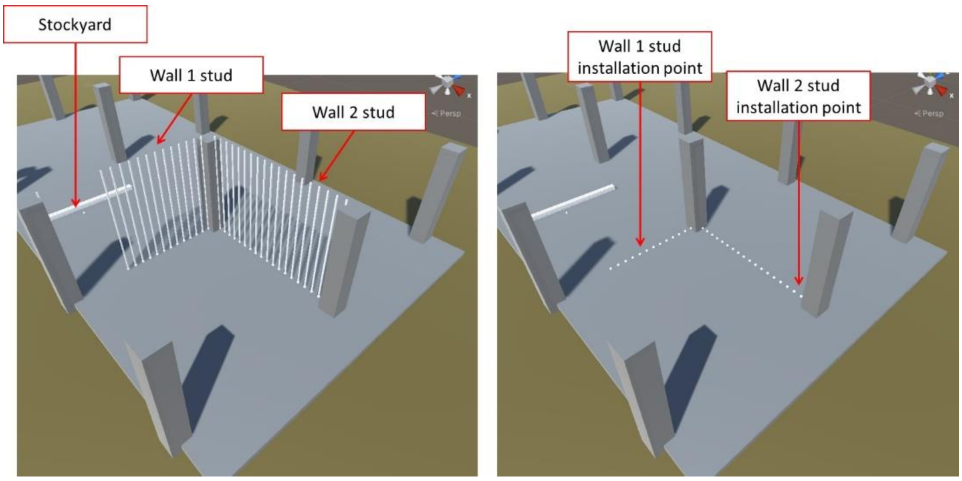


Fig. 1. Installation points for building components such as studs.

2.3. Determining the installation order of building components

Next, the installation order of the building components was determined, which consisted of two orders: the work order of the installation work group for walls and the installation order of each building component within the installation work group.

Figure 2 shows an example of an installation work group in an interior wall substrate. One installation work group comprised a series of walls. Figure 3 shows the relationship between the installation work group and the building component installation order within the group.

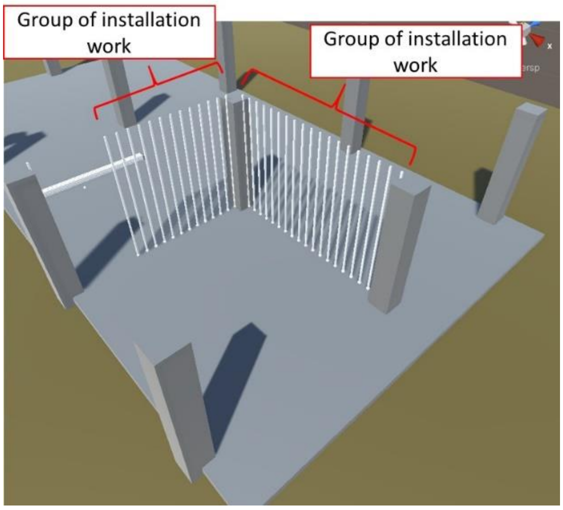


Fig. 2. Installation work group in an interior wall substrate.

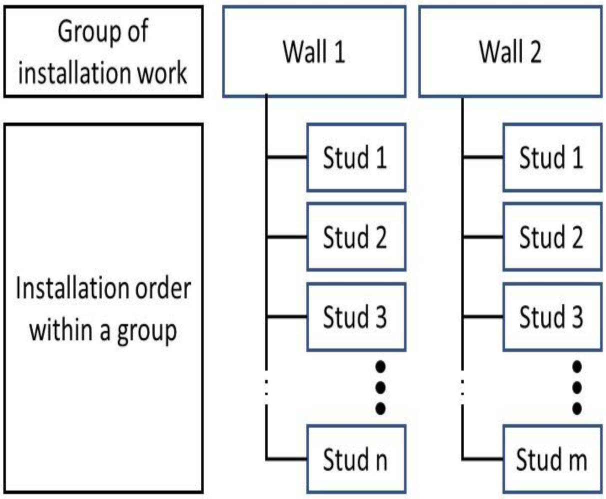


Fig. 3. Relationship between the installation work group and the building component installation order within the group.

2.4. Calculating the movement route of the worker

2.4.1. Creation of an agent that goes to its destination

In interior construction, a worker removes one component from a stockyard where building components are temporarily placed and carries it to the installation location of the building component. Therefore, the calculation of the movement route connecting the stockyard and the installation location of the building components is essential. In addition, this movement route should avoid the structural frame and installed studs. The movement path between these two points was calculated in this study using the NavMesh of Unity.

Figure 4 illustrates a schematic of the situation in which a worker moves to install a building component. The figure shows the route in which an agent (representing a worker) moves to a goal point (representing an installation location) while avoiding obstacles. The blue plane indicates the range within which a worker can move. The movable range of the workers was obtained using NavMesh.

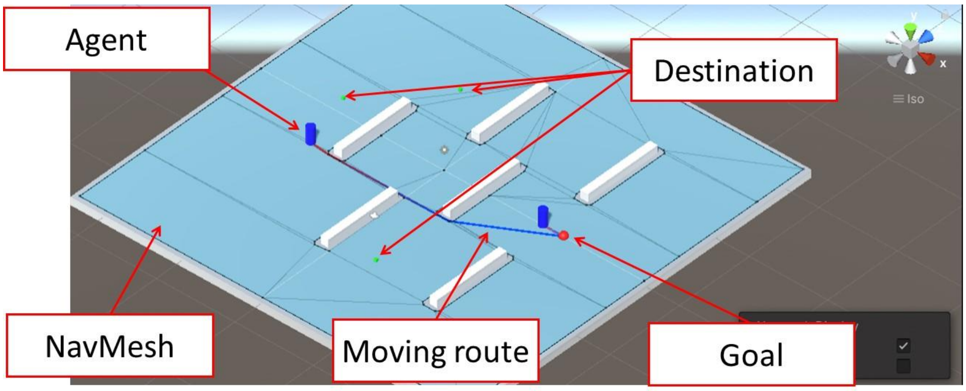


Fig. 4. Schematic of the situation in which a worker moves to install a building component.

Additionally, interior construction workers must place building components at different installation locations. Therefore, a mechanism by which the workers move toward the installation positions of the interior components must be introduced to reproduce the interior construction work in a virtual space in the aforementioned manner.

In this study, a procedure by which workers move toward this destination was developed, which consisted of two steps. The movements of the workers were reproduced by preparing a list of destinations and repeating the following two steps:

(1) The agent representing the worker moves toward the sphere representing the goal.

(2) When the agent touches the ball, the goal ball moves to its next destination.

Figure 5 shows the agents traveling to the four destinations. Four points (points 1 to 4) were set as destinations. The two agents headed toward the red ball which marked their goal. If one of the two agents touched the goal ball, the red ball moved to the next point. Figure 5 also shows the two agents moving to the next destination.

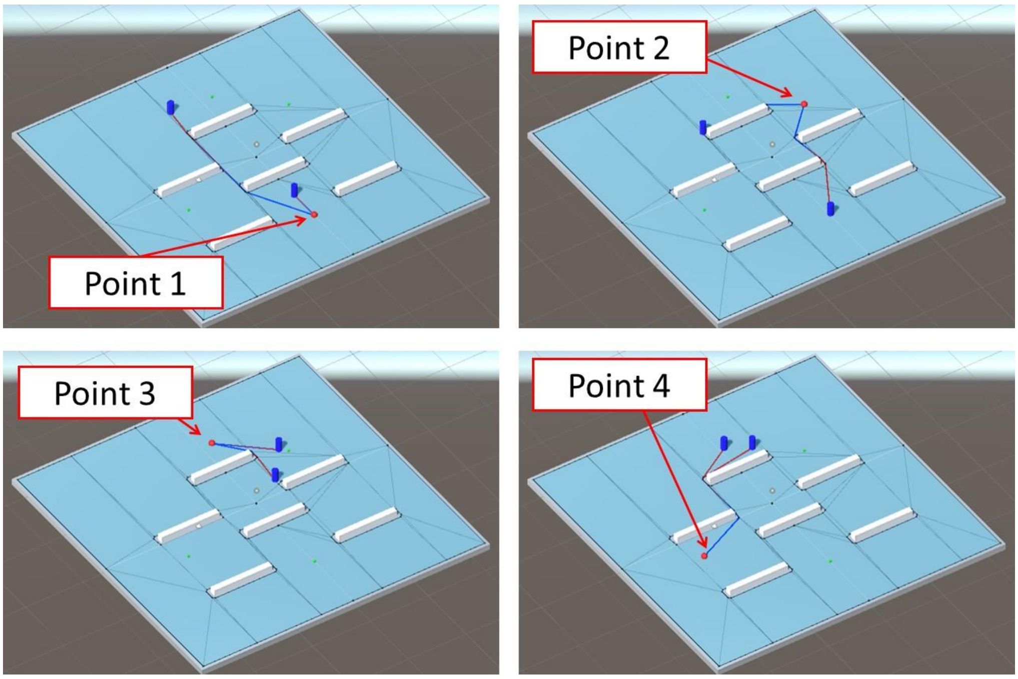


Fig. 5. Two agents traveling to four destinations.

2.4.2. Changing the moving area of the worker by installing building parts

In actual construction work, the range in which a worker can move changes when installing building components. For example, when installing a stud, workers cannot walk through the installation location of the stud.

Therefore, even in a virtual space, the range in which a worker can move each time a building component is installed must be changed. Based on this, a mechanism was introduced, which recalculates the range within which a worker can move each time a building component is installed.

Figure 6 shows the manner in which the range of the blue plane (which indicates the range in which the worker can move) changes with the installation of the studs. The lower right of Fig. 6 confirms that the wall is no longer passable owing to the installation of all studs that form the wall.

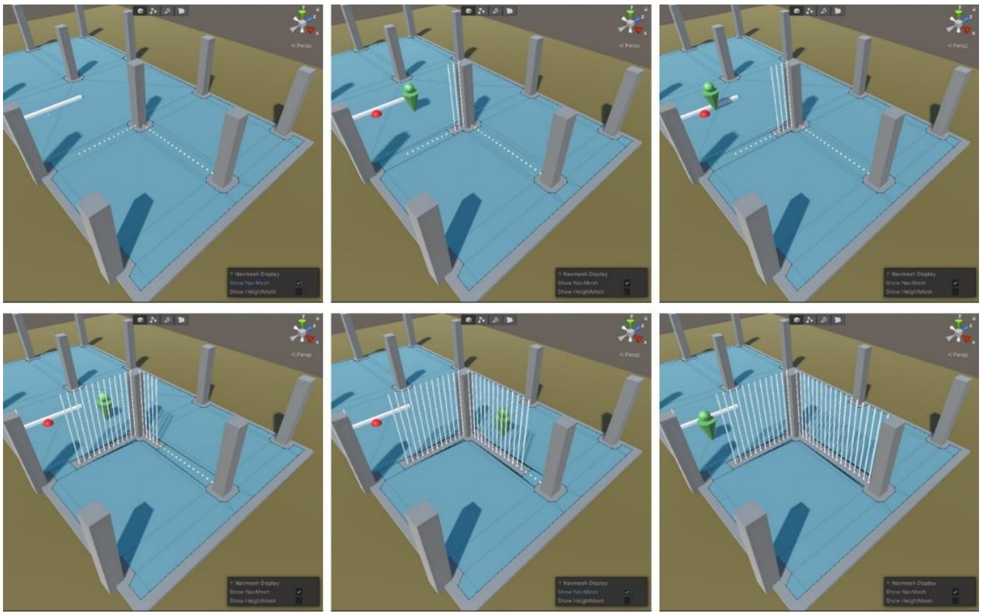


Fig. 6. Diagram showing the situation where the movable range of the worker changes due to the installation of studs.

2.5. Aggregating the total distance traveled

A worker in the virtual space records the process of assembling building components, while the system developed in this study calculates the distance traveled by the worker. Even when installing the same building components, the movement distance changes depending on the position of the stockyard and order of assembly. The working time was evaluated, and the efficient assembly order was calculated by comparing the moving distances.

Figure 7 shows the route taken by an agent representing a worker to install building components.

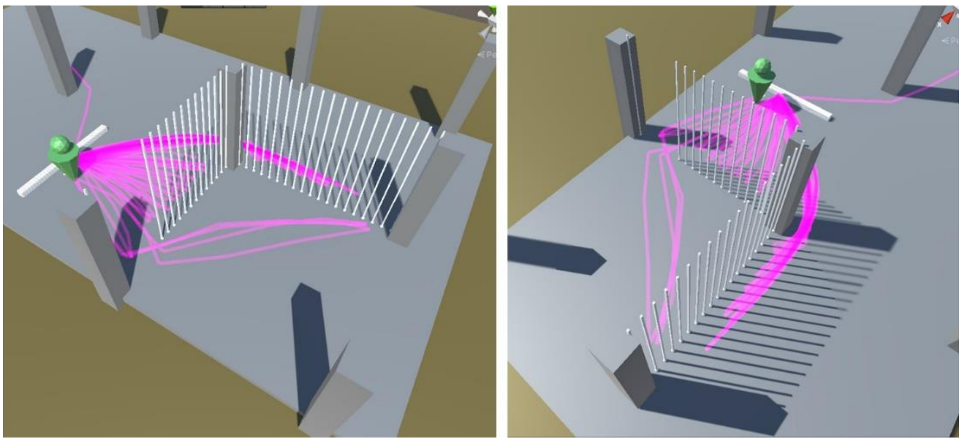


Fig. 7 Route taken by an agent to install a building component.

3. Analysis of changes in worker movement routes

Using the system described in the previous section, the changes in worker movement paths and differences in total worker movement distance owing to differences in the order of the building parts were analyzed. In particular, two orders of building walls were prepared, and the differences between them were analyzed.

The two walls were placed in a virtual space, as shown in Figure 8, which were labeled “Wall1” and “Wall2.” Subsequently, simulations performed for the following two assembly orders:

(1) Build Wall2 after building Wall1

(2) Build Wall1 following building Wall2

Figure 8 shows the movement route of the worker, which is indicated by the pink line. The left side of Fig. 8 shows the movement route when Wall2 was installed after Wall1, and the right side of Fig. 8 shows the movement path when Wall1 was installed after Wall2. To install Wall1 first, the situation in which the worker avoids Wall1 and moves away was confirmed.

Subsequently, the total travel distance was calculated based on the changes in the position coordinates of the workers’ in these two simulations. Table 1 lists the calculation results for the total distance moved. The procedure for creating Wall1 after Wall2 required a shorter total movement distance than that for creating Wall2 after Wall1. Because the number of components to be attached is the same, the difference in movement distance is considered to correspond to the difference in working time. Therefore, the procedure for creating Wall1 after Wall2 was more desirable.

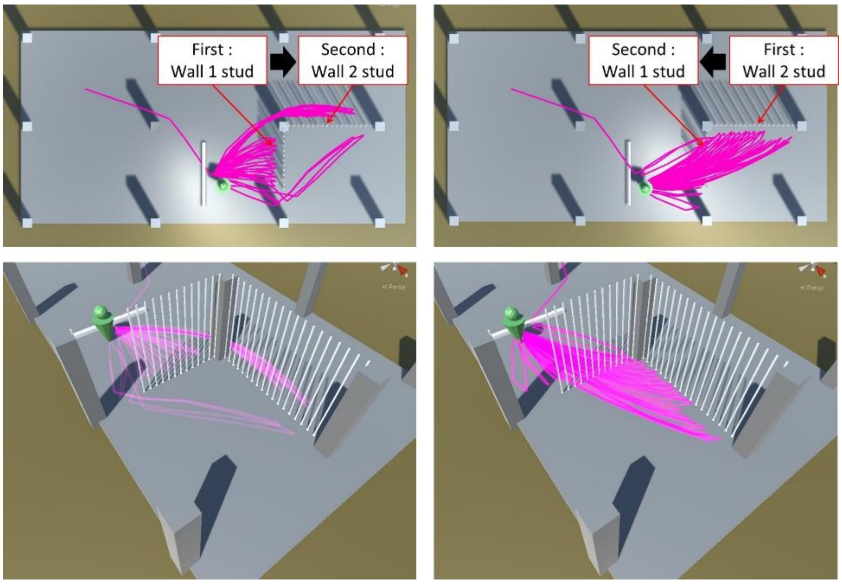


Fig. 8. Difference in worker movement routes due to differences in wall assembly order.

Table 1. Total movement distance

Order	Total travel distance
Wall1 → Wall2	567.7 m
Wall2 → Wall1	545.1 m

4. Application of work-order simulation method to repair work

4.1. Procedure for creating a three-dimensional (3D) model for the simulation of the work order for repair work

Although the number of new construction projects in Japan is decreasing, many renovation projects are required to maintain the enormous building stock. Therefore, the method described in the previous section was applied to the repair work.

For aforementioned application, a 3D simulation model must be created. The existing building are left in place, while new interior and facility work are conducted during the renovation. Therefore, the incorporation of the 3D shape of existing buildings into 3D models is essential. Accordingly, the 3D shape of the building was measured using a 3D laser scanner.

The procedure for creating a 3D model to simulate the work sequence for this repair work is as follows:

(1) the target location for the construction was measured using a 3D laser scanner.

(2) The density of point-cloud data was reduced

(3) The point-cloud data were converted into mesh data.

(4) The mesh and BIM data were integrated into the same coordinate system.

4.2. Creation of 3D models for 4D simulation

A 3D model was constructed for a 4D simulation of the repair work. The 3D model must be able to reproduce existing buildings. Hence, a 3D laser scanner was used to create a 3D model of an existing building. Figure 9 shows the point-cloud data obtained by measuring an existing building using a 3D laser scanner. Subsequently, mesh data based on the point-cloud data were obtained.

First, the point-cloud data were arranged at intervals of 2 cm, and their capacities were compressed. Subsequently, point-cloud data were converted into mesh data; Bentley's context capture was used. Figure 10 shows the created mesh data. The color of the point-cloud data is reflected in the texture of the mesh data.

Next, the mesh data were read in Unity, and NavMesh was used to calculate the range within which the worker could move. Figure 11 shows the calculation results; the blue plane represents the range within which a worker can walk.

After performing these processes, the BIM data for the partition wall installed in the area were read. Figure 12 shows the 3D model for simulating the installation at the base of the partition wall. The partition wall consists of five walls.

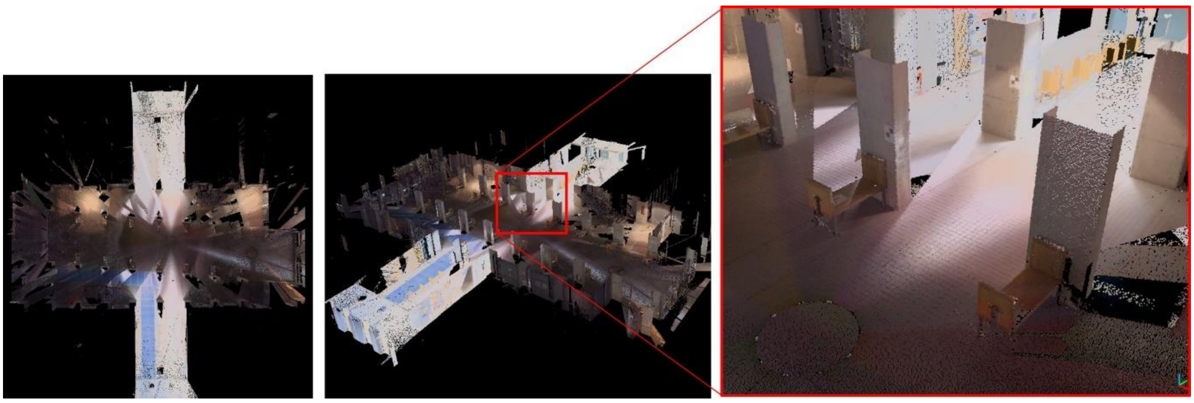


Fig. 9. Point-cloud data obtained by measuring an existing building with a 3D laser scanner.

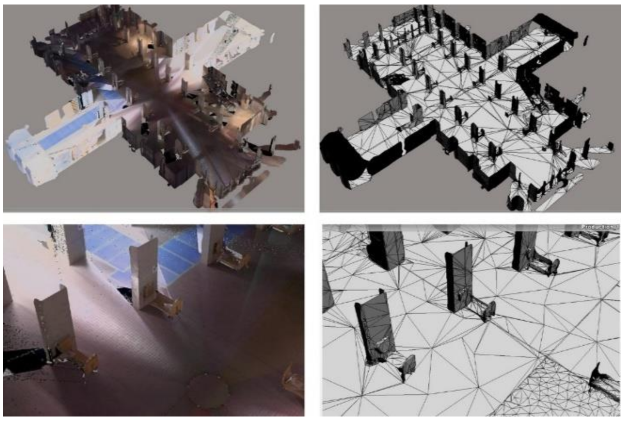


Fig. 10. Mesh data based on point-cloud data.

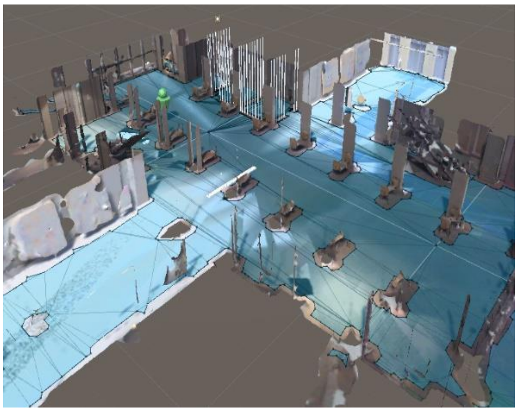


Fig. 11. Calculation results of the range in which the worker can move.

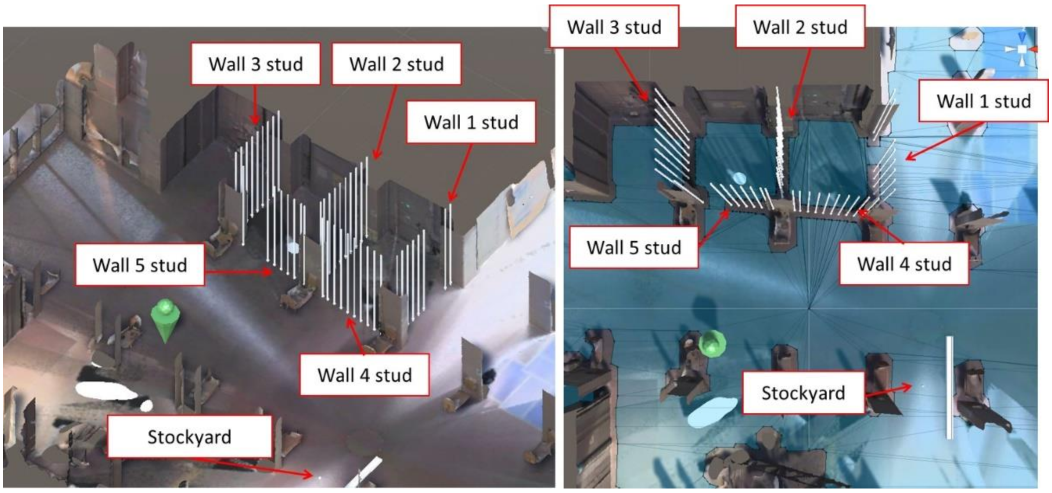


Fig. 12. 3D model for simulating the installation at the base of the partition wall.

4.3. Analysis of the difference in the total travel distance due to the difference in the assembly order

A simulation of the installation of the studs was conducted assuming that the retrofitting work was performed on an existing building. The 3D model described in the previous section was used. Five walls were used in the construction, which were labeled as Wall1, Wall2, Wall3, Wall4, and Wall5 (Fig. 12). First, the installation order of Wall1–Wall5 was simulated, and Figure 13 shows the agents placing studs according to their assembly orders. The manner in which the agent avoids the studs, pillars, and walls of existing buildings can be observed.

Subsequently, the change in the total moving distance due to the change in the installation order of the walls was analyzed. The following three patterns were used to prepare the installation orders of the walls:

(1) Wall1, Wall2, Wall3, Wall4, Wall5

(2) Wall4, Wall5, Wall1, Wall2, Wall3

(3) Wall3, Wall5, Wall2, Wall4, Wall1

Table 2 lists the total moving distance for each of the three installation orders and an image that visualizes the moving path of the worker.

The movement route was the shortest when the order of walls was Wall3, Wall5, Wall2, Wall4, and Wall1. This order applies to walls built the furthest from the stockyard. By installing them from the back, the previously installed studs were installed in an order that did not hinder worker movement. Therefore, this movement route was considered the shortest travel route.

However, when installing in order of Wall4, Wall5, Wall1, Wall2, and Wall3, the entire movement route of the workers was the longest. By installing the front wall first, workers had to make a long detour to move.

Thus, the method shown in this study can be appropriately calculated for new construction and renovation projects.

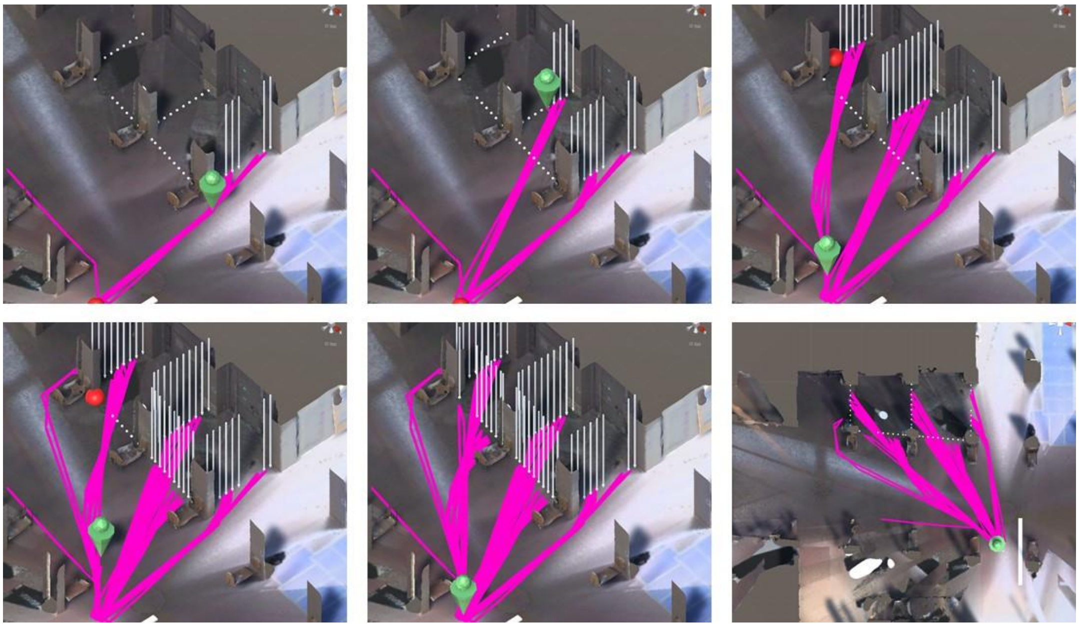
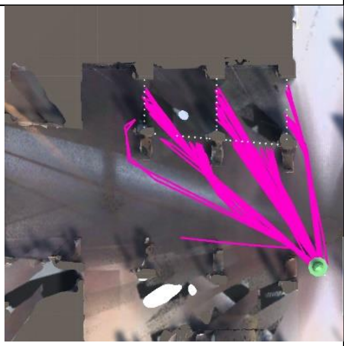
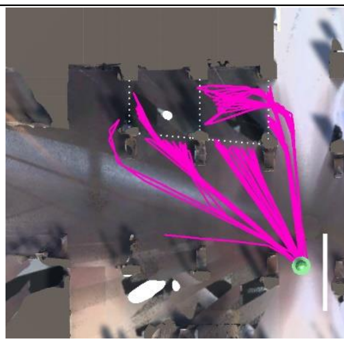
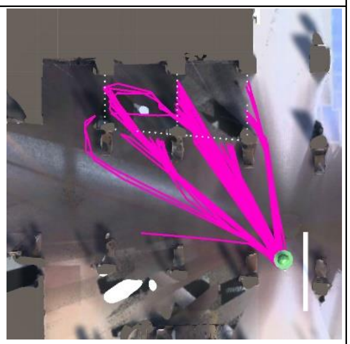


Fig. 13. Situation of agents placing the studs according to the assembly order.

Table 2. Total movement distance.

Assembly order	1,2,3,4,5	4,5,1,2,3	3,5,2,4,1
Total travel distance	916.6 m	937.3 m	889.5 m
Image of calculated route			

5. Conclusion

In this study, a simulation system was developed that determined the effect of changing the installation order of the building parts on the working time of the workers. The construction work was reproduced in a virtual space, and an agent that moved back and forth between the stockyard and construction site was created; this agent can move around and avoid the newly installed members. Consequently, a change in the movement route of workers can be simulated when the order of installation of the building parts is changed.

This simulation system was applied to install studs on partition walls during renovations. The change in the order in which the walls were installed at a virtual construction site changed the movement path of the workers. This simulation confirmed performing installation work from the placement side as much as possible is efficient.

References

[1] J. Jupp, "4D BIM for environmental planning and management," *Procedia Eng.*, vol. 180, pp. 190–201, 2017, doi: 10.1016/j.proeng.2017.04.178.

[2] A. L. C. Ciribini, S. Mastrolembo Ventura, and M. Paneroni, "Implementation of an interoperable process to optimise design and construction phases of a residential building: A BIM Pilot Project," *Autom. Constr.*, vol. 71, pp. 62–73, 2016, doi: 10.1016/j.autcon.2016.03.005.

[3] V. Getulia and P. Capone, "Computational workspaces management: A workflow to integrate workspaces dynamic planning with 4D BIM," *35th Int. Symp. Autom. Robot. Constr. (ISARC)*, pp. 1117–1124, 2018, doi: 10.22260/ISARC2018/0155.

[4] K.-T. Pham, D.-N. Vu, P. L. H. Hong, and C. Park, "4D-BIM-based workspace planning for temporary safety facilities in construction SMEs," *Int. J. Environ. Res. Public Health*, vol. 17, no. 10, 3403, 2020, doi:10.3390/ijerph17103403.

[5] M. Afzal and M. T. Shafiq, "Evaluating 4D-BIM and VR for effective safety communication and training: A case study of multilingual construction job-site crew," *Buildings*, vol. 11, 319, 2021, doi:10.3390/buildings11080319.

[6] A. N. Tak, H. Taghaddos, A. Mousaei, A. Bolourani, and U. Hermann, "BIM-based 4D mobile crane simulation and onsite operation management," *Autom. Constr.*, vol.128, 103766, 2021, doi:10.1016/j.autcon.2021.103766.

[7] C. Boton, "Supporting constructability analysis meetings with Immersive Virtual Reality-based collaborative BIM 4D simulation," *Autom. Constr.*, vol. 96, pp. 1–15, 2018, doi: 10.1016/j.autcon.2018.08.020.

[8] J. Lee and J. Kim, "BIM-based 4D simulation to improve module manufacturing productivity for sustainable building projects," *Sustainability*, vol. 9, no. 3, 426, 2017, doi: 10.3390/su9030426.

[9] C. Boton, S. Kubicki, and G. Halin, "The challenge of level of development in 4D/BIM simulation across AEC project lifecyle. A Case Study," *Procedia Eng.*, vol. 123, pp. 59–67, 2015, doi: 10.1016/j.proeng.2015.10.058.

[10] B. Butkovic and D. Heesom, " Towards a framework for multi-LOD 4D BIM simulations," *Int. Res. Conf. 2017: Shaping Tommorrow's Built Environ. Conf. Proc.*, pp. 578–586, 2017.

[11] P. Farnood Ahmadia and M. Arashpourb, "An analysis of 4D-BIM construction planning: Advantages, risks and challenges," *Proc. 37th Int. Symp. Autom. Robot. Constr. (ISARC)*, pp. 163–170, 2020, doi: 10.22260/ISARC2020/0025.

[12] O. Doukari, B. Seck, and D. Greenwood, "The creation of construction schedules in 4D BIM: A comparison of conventional and automated approaches," *Buildings*, vol. 12, no. 8, 1145, 2022, doi:10.3390/buildings12081145.

Potential of structural multi-objective optimization of reinforced concrete slabs in the context of sustainable development

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Abstract
Reducing material usage and ensuring adequate performance and safety of bearing structures became fundamental aspects of modern engineering design and optimization. Reinforced concrete slabs in multi-storey buildings transfer vertical floor loads and horizontal shear loads to other bearing elements, such as walls, columns, or beams. They provide stability and contribute to overall structural integrity. Especially in large structures with a repeating floor plan over several storeys, material consumption in reinforced concrete slabs can add up quickly. Structural optimization aimed at reducing material usage can provide significant benefits in terms of sustainability and conservation of resources. This paper presents a recommendation for a framework of structural multi-objective optimization (MOO) of storey slabs made of reinforced concrete and highlights the need for efficient use of resources, especially in the context of sustainable development. A case study of the suggested structural MOO-framework is carried out on an existing concrete slab of a large residential building using "*C-SLOP"* (*C*oncrete *SL*ab *OP*timizer), a tool developed for this purpose. Using the case study results as a basis, input parameters for the optimization process were calibrated in order to obtain more realistic results, to consider the structural aspects from the execution phase and to find an optimized design solution. The paper highlights the importance of multi-objective structural optimization of simple common bearing parts, such as reinforced concrete slabs, in early stages of structural design and emphasizes the potential for material savings in the construction industry.

Keywords: parametric modelling, structural multi-objective optimization, reinforced concrete slabs

1. Introduction

Concrete is well known as the most used material in construction industry due to its durability and strength, however its consumption is responsible at least for 8.6% of all anthropogenic CO_2 emissions [1, 2]. Despite its popularity, there is a significant lack of parametrical structural optimization of common bearing parts and elements during the civil engineering planning process [3]. Even though such parametric optimization and decision support (POD) model framework has proven to be very effective to identify potential savings in terms of the economic and environmental resource efficiency of structural objects and buildings at a very early design stage [4] by generating solutions with an aid of multi-objective optimization (MOO) process and investigating them on quantified findings, while still ensuring the strength and safety of the structure [5].

This paper presents a novel pipeline of implementation of structural MOO process into the daily based task of structural engineering, such as design of reinforced concrete storey slabs with repeating floor plan. For this occasion, a tool called *C-SLOP* (*C*oncrete *SL*ab *OP*timizer) has been developed within this research. This paper aims to present the framework of the above-mentioned tool and to emphasize the potential for material savings in the construction industry, especially of common bearing parts and elements. As test case, an already built up real reinforced concrete slab of a large residential building will be examined with *C-SLOP*. In order to find an optimized design solution and to consider the structural aspects from the execution phase, the results of the examined case study were compared with the real results. The examination of deviation between both cases helped to calibrate input parameters for the MOO process and get more realistic results.

2. Framework

The computational framework of *C-SLOP* finds itself within the CAD-Software *Rhinoceros3D* [6]. Its visual programming language *Grasshopper3D* [6] allows the creation of complex parametric algorithms and power them with generative evolutionary solvers, e.g. Octopus [7], which was used within *C-SLOP´*s framework described in following chapters. The finite element analysis (FEA) is performed with an aid of Grasshopper´s plugin *Karamba3D* [8].

2.1. Structural FE model and analysis

The structural model is represented by the 2D finite element (FE), located parallel to the cartesian XY-plane, whereby the height (Z-coordinate) can be chosen freely by the user. Within the slab geometry, the slab openings can also be defined (e.g., lift shaft, infrastructure shaft etc.). Fig. 1(a). exemplarily depicts a slab geometry with opening and line support definition in *C-SLOP*. The walls are represented by line support definition along the wall-slab connection. The line support definition includes free degree of freedom (DOF) for rotation around local x-axis and translation perpendicular to wall-slab connection line (local y-axis). The translation along global Z-axis and along local x-axis of the connection is rigid. Fig. 1(b) depicts the described line support connection at the reference FE surface of the slab.

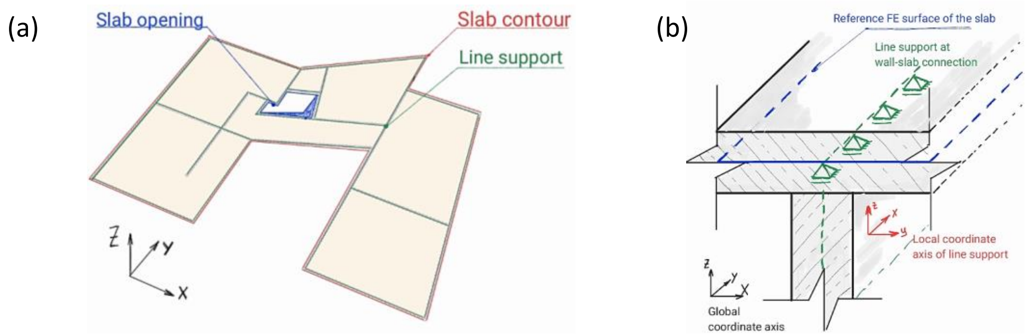

Fig. 1. (a) Slab geometry with openings and line supports; (b) wall-slab connection.

Within the process of the structural analysis of reinforced concrete slabs, it´s significant to consider the load distribution along the whole slab´s geometry. Thus, the slab is normally separated into individual sections, so called *fields*. This separation allows to apply different loads and their combination independently on every slab field. As also envisaged by the standards and codes, it´s mandatory to consider all possible (advantageous and disadvantageous) load combinations scenarios in structural analysis due to their effects on the structural performance. Thus, some loads can act in different directions and partially cancel other loads (advantageous). Disadvantageous loads act accordingly in the same direction and produce grater level of stress and deflection. Building codes and standards, such as Eurocode, address this problem with so called safety factors $\gamma_{G,dis}$, $\gamma_{G,adv}$ for permanent and $\gamma_{Q,dis}$, $\gamma_{Q,adv}$ for variable loads. Fig. 2(a) depicts a possible contribution of the field in a slab. The application of different load combination scenarios for this exemplary field distribution is shown in Fig. 2(b).

Structural analysis is performed for all possible load combinations in ultimate and serviceability limit states (ULS & SLS). The long-term deflection of the slab, which includes the effects of creep and dwindle of concrete, is calculated in SLS quasi-permanent.

As a part of structural analysis, the required amount of steel reinforcement per layer and direction is calculated with the *Karamba3D´s* component "*Optimize Reinforcement"* [9], based on the sandwich model approach of Marti [10, 11]. However, this approach doesn´t cover the amount of needed overlap, edge, and connection reinforcement.

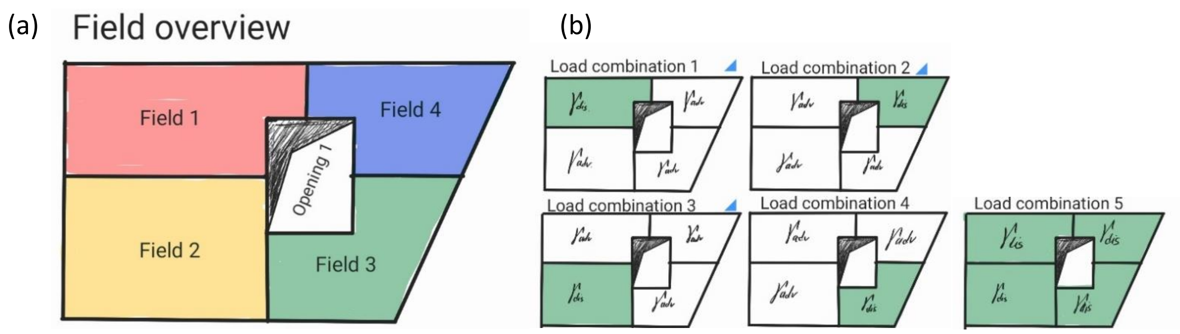

Fig. 2. (a) Slab field overview; (b) Different load combinations on slab fields.

2.2. Optimization

As mentioned before, the novel approach of MOO is used within the described framework. Variable inputs in *C-SLOP* are listed in Table 1.

Table 1. Input parameter of the test case

Name	Description
Variables:	
Concrete sort	C20/25, C25/30, C30/37, C35/45, C40/50, C50/60
Slab thickness	18cm, 19cm, 20cm, 21cm, 22cm, 23cm, …, 60cm
1st bottom main grid of reinforcement*	Ø8/25, Ø8/20, Ø10/25, Ø8/16, Ø10/20, Ø12/25, …
2nd bottom main grid of reinforcement*	Ø8/25, Ø8/20, Ø10/25, Ø8/16, Ø10/20, Ø12/25, …
1st upper main grid of reinforcement*	Ø8/25, Ø8/20, Ø10/25, Ø8/16, Ø10/20, Ø12/25, …
2nd upper main grid of reinforcement*	Ø8/25, Ø8/20, Ø10/25, Ø8/16, Ø10/20, Ø12/25, …
Goals:	
Minimization of used concrete mass	Reduction of environmental and cost impact
Minimization of used steel reinforcement mass ($A_{s,total}$ in Fig. 3)	Reduction of environmental and cost impact
Deterioration of concrete sort	Reduction of environmental and cost impact
Maximization of the step of rebars in the main grid	Minimization of time effort in reinforcing process

* Only standard-complaint reinforcement grids are considered. It means, that only main grids with provided amount of reinforcement $A_{s,prov,main}$ greater than the minimal required amount of reinforcement $A_{s,req,min}$ acc. to Eurocode 2 [12, 13] are used as variables in MOO-process. This approach allows to consider all possible variants of structure, where the usage of heavier main grid could lead to smaller usage of additional reinforcement $A_{s,req,add}$ and overall used steel reinforcement material $A_{s,total} = A_{s,prov,main} + A_{s,req,add} + A_{s,constr}$. Constructive reinforcement $A_{s,constr}$ describes edge, lap joints and connection reinforcement. Fig. 3 depicts other above-mentioned definitions of steel reinforcement amount (exemplary on two-fielded slab strip spanned in one direction).

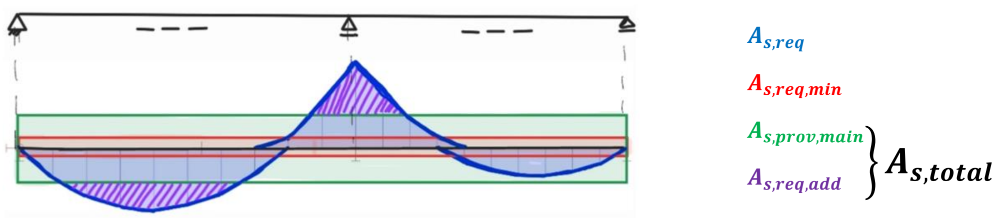

Fig. 3. Definition of the steel reinforcement amounts.

The SLS-criteria in characteristic (initial deflection) and quasi-permanent (long-term deflection) according to Eurocode 2 take role as constraints during the MOO-process.

3. Test case

As already mentioned before, the test case study is applied to already built-up residential project. It contains a concrete floor slab with 10 repeating storeys. The dimensions of the structural FE-model are depicted in Fig. 4.

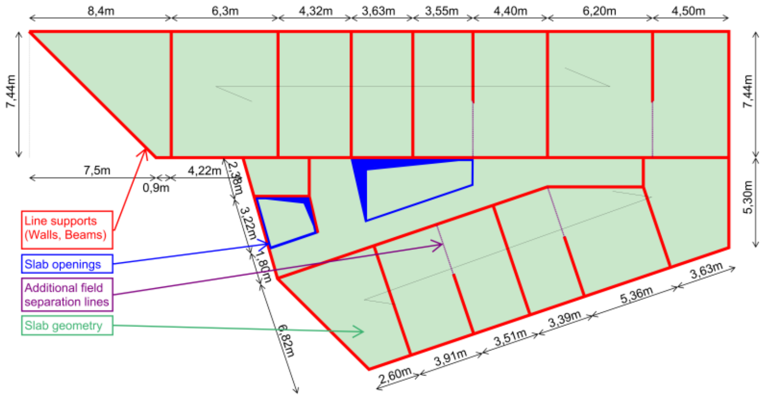

Fig. 4. Dimensions of the structural FE-model of the test case slab geometry

Generative structural multi-objective optimization took place with the input data and load definition listed in Table 2. The local axis of the reinforcement direction is aligned in such way, that the shortest span length of the field represents the direction of the 1st rebar layer. The 2nd rebar layer is located crosswise.

Table 2. Input parameter of the test case

Name	Description
Variables:	
Range of applied concrete sort	C25/30, C30/37, C35/45, C40/50, C45/55, C50/60
Range of applied slab thickness	18cm, 19cm, 20cm, 21cm, 22cm, 23cm, …, 40cm
Range of applied amount of reinforcement steel as the main grid $A_{s,prov,main}$	Minimal standard acceptable main grid, …, Ø20/15
Constant values:	
Steel sort of the reinforcement	B550B acc. To Eurocode 2 [14, 15]
Loads:	
Self-weight	Self-weight of the structure is calculated automatically within the FE-Analysis of Karamba3D
Dead load	Areal load 2,50 kN/m², permanent loads
Payloads	Areal load 3,00 kN/m², variable loads
FE-mesh resolution	~0,25 meter
MOO-parameters:	
Elitism	0.500
Mutation probability	0.200
Crossover rate	0.800
Population size	100
Maximal generations	20

4. Results

Due to competing properties of possible optimal solutions, no overall optimal variant of the structure can be found. Therefore, the so called pareto front is examined and compared. Pareto solution of the test case are listed in Table 3 and depicted in Fig. 5 with the dependence on concrete sort (*CS*), slab thickness $h\ [cm]$, 1st upper rebar layer (*1+*), 2nd upper rebar layer (*2+*), 2nd button rebar layer (*2-*) and 1st button rebar layer (*1-*).

Table 3. Input parameter of the test case

CS_h_*1+_2+_2-_1-*	Needed concrete mass [kg] and [% from the lowest]		Needed steel mass [kg] and [% from the lowest]	
C25/30_18_*Ø8/23_Ø8/23_Ø8/23_Ø8/23*	225587	100%	4115	100%
C25/30_18_*Ø8/23_Ø8/23_Ø8/22_Ø8/23*	225587	100%	4149	101%
C25/30_18_*Ø10/25_Ø8/23_Ø8/23_Ø8/23*	225587	100%	4520	110%
C25/30_18_*Ø10/25_Ø8/23_Ø10/25_Ø8/23*	225587	100%	4880	119%
C45/55_18_*Ø12/24_Ø12/25_Ø10/25_Ø10/25*	225587	100%	7229	176%
C45/55_18_*Ø12/24_Ø12/23_Ø10/25_Ø10/25*	225587	100%	7438	181%
C35/45_19_*Ø10/25_Ø10/23_Ø10/24_Ø10/25*	238120	106%	5936	144%
C30/37_19_*Ø10/25_Ø14/25_Ø14/22_Ø12/25*	238120	106%	9494	231%
C30/37_21_*Ø10/25_Ø10/23_Ø10/24_Ø10/25*	263185	117%	5925	144%
C25/30_24_*Ø10/24_Ø10/25_Ø10/25_Ø10/25*	300783	133%	5789	141%

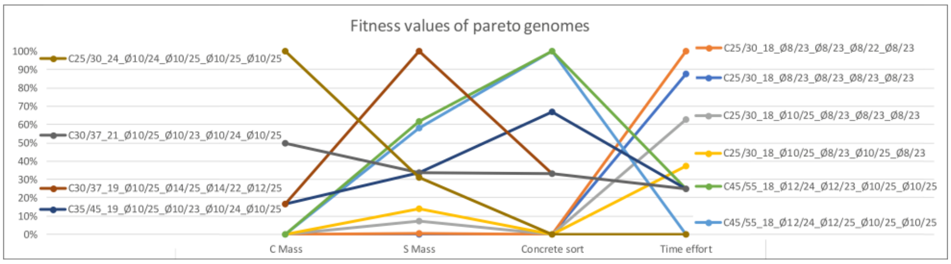

Fig. 5. Fitness values of pareto genomes

Due to small differences in the rebar step (from 22cm to 25cm) and accumulating time effort, one can neglect this objective. Based on this accusation, one variant may be chosen as optimal and be used for further analysis – the slab with C25/30 concrete sort and 18 [cm] slab thickness. This variant is compared to the existing slab which is build out of C25/30 concrete sort with 20 [cm] thickness. For more realistic comparison of overall used mass of reinforcement steel, reinforcement plans of the *C25/30_18* slab are created with the consideration of *edge, overlap, and connection reinforcement*. This variant is called *C25/30_18_realistic* in the further comparison which is listed in Table 4.

Table 4. Comparison of the already built-up slab *C25/30_20*, optimal solution of C-SLOP *C25/30_18* and practical variant of the optimum *C25/30_18_realistic*.

Name	Concrete volume [m³]	Mass of used reinforcement steel [kg]	Degree of reinforcement [kg/m³]
Built-up *C25/30_20*	109,3	6630	60,7
Optimum of the test case *C25/30_18*	98,37	4115	41,8
Realistically designed *C25/30_18_realisitc*	98,37	6627	67,4

5. Conclusion

The primary objective of the research presented in this paper is to introduce a novel methodology for the optimization of reinforced concrete slabs using the developed tool *C-SLOP* (*C*oncrete *SL*ab *OP*timizer). The tool is aided by parametric modelling, structural finite element analysis and multi-objective optimization. To prove its functionality, a test case was conducted on an already built-up concrete slab with repeating floor plans. The results of the optimization process were analyzed and lead to following conclusions:

- Comparing the thickness of existing and optimized slab, one may have reduced it from 20 cm to 18 cm without higher reinforcement effort (see also Table 4). Such reduction in thickness of the slab could have led to significant lower environmental and price impacts due to material saving, considering the repeating geometry of the slab over 10 storeys of the building (almost 11 m³ concrete per slab and 110 m³ in total).

- However, the calculated needed amount of reinforce steel is significantly lower than the realistically imitated structurally designed model of the same slab with 18 cm thickness. This discrepancy occurs due to the lacking functionality (consideration of overlap, edge, and connection reinforcement) of used framework for the calculation of the needed rebar amount. Therefore, the actual amount of steel required for the optimized slab geometry is 61% higher than the calculated one (6627 kg to 4115 kg).
- The case study has estimated that the difference in the rebar step between all pareto optimal solutions is not significant for this exact slab geometry (see also Fig. 4).

Summarized, the *C-SLOP* tool could potentially lead to substantial material savings and lower environmental impact providing several possible solutions and establishing the range for decision making support. However, further research is needed to improve tool´s functionality regarding more precise output for amount of reinforced steel. Occasionally, the computational framework of *C-SLOP* may be included in common structural FE software and become an everyday habit in the design process.

Acknowledgement

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References

[1] The International Energy Agency (IEA), *World Energy Outlook 2015,* https://www.iea.org/reports/world-energy-outlook-2015 (Access date: 21.02.2023).
[2] S. A. Miller, A. Horvath, and P. J. M. Monteiro, “Readily implementable techniques can cut annual CO 2 emissions from the production of concrete by over 20%,” *Environ. Res. Lett.*, vol. 11, p. 74029, 2016, doi: 10.1088/1748-9326/11/7/074029.
[3] D. Daleyev, J. Reisinger, and M. Königsberger, “Potential of Parametric Modeling for Structural Optimization A Variant Study of Industrial Buildings with Different Timber Structure Systems,” in *Proceedings of the Creative Construction e-Conference 2022.* Online: Budapest University of Technology and Economics, 2022, pp. 328–333, doi: 10.3311/CCC2022-042.
[4] J. Reisinger, S. Kugler, I. Kovacic, and M. Knoll, “Parametric Optimization and Decision Support Model Framework for Life Cycle Cost Analysis and Life Cycle Assessment of Flexible Industrial Building Structures Integrating Production Planning,” *Buildings*, vol. 12, p. 162, 2022, doi: 10.3390/buildings12020162.
[5] M. A. Zahlbruckner, J. Reisinger, X. Wang-Sukalia, P. Kán, M. Knoll, and I. Kovacic, et al., “Evaluation of parametric multi-objective optimization and decision support tool for flexible industrial building design,” in *Proceedings of the 2022 European Conference on Computing in Construction:* University of Turin, 2022, doi: 10.35490/EC3.2022.202.
[6] Robert McNeel & Associates, *Rhinoceros3D & Grasshopper3D,* https://www.rhino3d.com/ (Access date: 13.03.2023).
[7] R. Vierlinger, *Octopus,* https://www.food4rhino.com/en/app/octopus (Access date: 13.03.2023).
[8] C. Preisinger, “Linking Structure and Parametric Geometry,” *Archit Design*, vol. 83, pp. 110–113, 2013, doi: 10.1002/ad.1564.
[9] C. Preisinger, *Optimize Reinforcement,* https://manual.karamba3d.com/3-in-depth-component-reference/3.5-algorithms/3.5.11-optimize-reinforcement (Access date: 20.03.2023).
[10] J. Blaauwendraad, *Plates and FEM. Surprises and Pitfalls.* Dordrecht. Springer, 2010.
[11] *Practitioners' guide to finite element modelling of reinforced concrete structures. State-of-art report prepared by Task Group 4.4.* Lausanne. International Federation for Structural Concrete (fib), 2008.
[12] Austrian Standards, *Eurocode 2: Design of concrete structures - Part 1-1: General rules and rules for buildings (consolidated version).* ÖNORM EN 1992-1-1, Feb, 2015, https://shop.austrian-standards.at/action/en/public/details/536661/OENORM_EN_1992-1-1_2015_02_15 (Access date: 20.03.2023).
[13] Austrian Standards, *Eurocode 2 - Design of concrete structures - Part 1-1: General rules and rules for buildings - National specifications concerning ÖNORM EN 1992-1-1, national commnts and national supplements.* ÖNORM B 1992-1-1, Jan, 2018, https://shop.austrian-standards.at/action/en/public/details/621961/OENORM_B_1992-1-1_2018_01_01 (Access date: 20.03.2023).
[14] Austrian Standards, *Eurocode 2: Design of concrete structures - Part 1-1: General rules and rules for buildings (consolidated version).* ÖNORM EN 1992-1-1, Feb, 2015.
[15] Austrian Standards, *Eurocode 2 - Design of concrete structures - Part 1-1: General rules and rules for buildings - National specifications concerning ÖNORM EN 1992-1-1, national commnts and national supplements.* ÖNORM B 1992-1-1, Jan, 2018.

CONSTRUCTION EQUIPMENT EMISSION CONTROL STATUS, POLICIES, AND REGULATIONS IN CHINA

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Abstract

China is the largest construction market in the world and keeps growing at about 5% per year in terms of construction market value. China's construction equipment is also the world's largest in terms of units of sales. Most of the equipment units are diesel powered due to need for high power output and the diesel engines emit toxic pollutants of particulate matters (PM), Nitrogen oxides (NOx), unburned hydrocarbons (HC), and carbon monoxide (CO) of large amounts, which are proved to be detrimental to human health. There has been a pressing need for the government to control emissions from diesel engines by implementing stringent requirements on emission standards and regulating the manufacturing and operations of construction equipment in a progressive approach. This paper conducts a review of China's current emission status of construction equipment, emission standards for diesel equipment engines and equipment operations, a summary of China's related emission regulation policies on construction equipment is made, and a comparison analysis is conducted with some developed regions such as the United States and EU countries.

Keywords: construction equipment, exhaust emissions, emission standards, regulatory control, comparative study.

1. Construction equipment market in China

Construction equipment is the essential engineering equipment required for construction works, including hydraulic excavators, bulldozers, loaders, graders, pavers, road rollers, cranes and forklifts. China has been holding one of the leading positions in the global construction equipment market. Data shows that compared with other regions, China's growth rate of equipment manufacturing has steadily increased from 2015 to 2018. In 2019, China's construction equipment market surpassed North America, reaching 169.38 thousand units, ranking first in the world (iimedia, 2019).

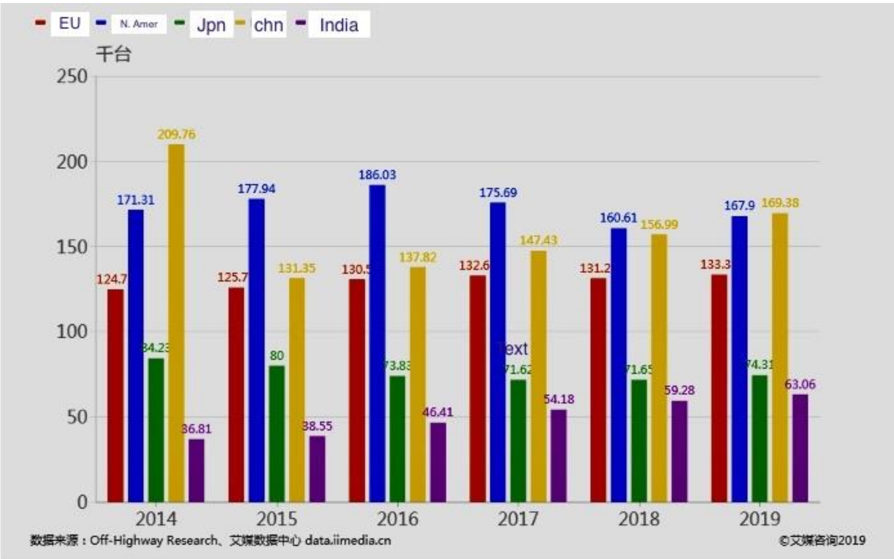

Fig. 1. Global construction equipment market distribution (Thousands of units)

According to the Annual Report on China Mobile Source Environmental Management (MEE, 2022), non-mobile sources in China emitted 168 thousand tons of SO^2, 429 tons of HC, 4789 tons of NOx, and 234 Tons of PM. In terms of percentage values in emissions from mobile sources, 26% of HC, 30% of NOx, and 32.1% of PM are from construction equipment. In 2021, in the registration database of nonroad machineries in China, there are 197 thousand excavators, 137 thousand loaders, 13 thousand rollers, 4 thousand bulldozers, 2 thousand pavers, 1 thousand graders. Among the construction equipment, excavators emitted 37%, loaders emitted 44.1% of HC; loaders emitted 42%, and excavators emitted 36.3% of NOx; Excavators emitted 52.9%, and loaders emitted 35.9% of PM, which shows excavators and loaders are equipment types emitting the most criteria pollutants during operations. Around half of the pollutants from construction equipment are emitted from China non-road Tier-3 equipment and others from Tier-2 and Tier-1 and pre-Tier 1 equipment. Since China Tier-4 non-road mobile diesel engine standard came into effects in Dec 2022, there are very few Tier-4 equipment units in the market. Most of the in-service construction equipment unit in China are of high-pollution old generations.

2. Emission standards of construction equipment

Diesel engine emissions are measured on an engine dynamometer over a standardized emission test cycle to simulate the real word operations in the laboratory (DieselNet, 2023). Portable emission measurement systems (PEMS) can also be used to verify the emissions for certification or for in-service conformity (ISC) testing in real operations of the equipment. Diesel engine regulatory limits are expressed in grams of pollutant per kWh, for different categories of engine horsepower.

According to the "Emission Limits and Measurement Methods of Diesel Engine Exhaust Pollutants for Non Road Mobile Machinery (China Phase 3 and 4)" (GB20891-2014) issued by the Ministry of Ecology and Environment (MEE, 2023a; MEE, 2023c), China's emission standards for non-road mobile machinery for Tier 3 engine was Implemented on 1 October, 2015. MEE later revised GB20891 and issued technical standard “Emissions control technical requirements of non-road diesel mobile machinery” (HJ 1014-2020) in 2021. After some delays, China Tier-4 standard on non-road diesel engines came into effect on 1 December, 2022.

GB20891-2014 Tier 4 standard mainly tightens the limit requirements for NOx and particulate matter. For HC and NOx, Tier 4 has made more detailed requirements, and the emission limits have been lowered. For engine power of $56<P<75$, the combined emission limit of HC + NOx specified by Tier 4 is reduced by 26% compared with Tier 3; for $75<P<130$, the reduction is 13%; for $130<P<560$, the reduction is 45%; when $P>560$, the reduction is 39%. For pollutant emission, after the implementation of the Tier 4 standard, the PM levels of diesel engines above 37kW have been reduced to varying degrees, especially the reduction of particulate matter. The PM limit for equipment above 560kW becomes 50% of the original limit. From 37kW to 560 kW, the PM limit is about 10% of the original limit.

HJ 1014-2020 standard further improved the specifications and technical tests of Tier 4, such as adding detailed specifications for non-road transient cycle (NRTC) and portable emissions measurement system (PEMS), it also introduced the PN limit and test requirements for wall flow diesel particulate filter (DPF). At the same time, the requirements for the emission warranty period have been extended. If the emission-related components fail or are damaged during the warranty period, causing the emission control system to fail, or the vehicle emission exceeds the limit requirements of this standard, the manufacturer should bear the relevant maintenance costs. HJ 1014-2020 requires Tier 4 standards to be implemented from December 1, 2022. All non-road mobile machinery below 560 kW (including 560 kW) manufactured, imported and sold and the diesel engines installed there-on shall meet the requirements of Tier 4 standards.

Major global economies have already imposed legislative restrictions on pollutant emissions from construction equipment (categorized as non-road diesel engines in general), and established a phase-wise progressive tightening of emissions standards. In US, EPA Tier 4 was implemented from 2008 to 2015 (Tier 4i: 2008-2014, Tier 4F 2014+). On September 14, 2016, the European Union issued the latest Stage V pollutant emission standards for non-road mobile machinery, namely Regulation EU2016/1628. Subsequently, supporting regulations were successively issued, including technical requirements, vehicle management requirements and document management requirements.

The updated non-road standards adopted by the United States, the European Union, Japan and China are US Tier 4, EU Stage V, Japan 2016 and China non-road Tier 4. The detailed regulatory limits on the emissions of various pollutants are shown in Table 1 for comparison.

Table 1. Comparison of Diesel-engine emissions standards of non-road mobile engines: China and overseas

Engine Power (kW)	Region	CO (g/kWh)	HC (g/kWh)	NOx (g/kWh)	NMHC (g/kWh)	PM (g/kWh)	PN (#/kWh)	Smoke
kW < 8	US	8.0		7.5		0.4		
	EU	5.5	7.5			0.4	-	
	JP							
	China Tier 3	5.5	7.5			0.6		
	China Tier 4	5.5	7.5			0.6	5×10^{12}	
8 ≤ kW < 19	US	6.6		7.5		0.4		
	EU	5.5	7.5			0.4	-	
	JP							
	China Tier 3	5.5	7.5			0.6		
	China Tier 4	5.5	7.5			0.6	5×10^{12}	
19≤P<37	US	5	-	4.7		0.03		
	EU	5	4.7			0.015	1×10^{12}	
	JP	5		4	0.7			25
	China Tier 3	5.5	7.5			0.6		
	China Tier 4	5.5	7.5			0.6	5×10^{12}	
37≤P<56	US	5	-	4.7		0.03		
	EU	5	4.7			0.015	1×10^{12}	
	JP	5		4	0.7			25
	China Tier 3	5	4.7			0.4		
	China Tier 4	5	4.7			0.025	5×10^{12}	
56≤P<75	US	5	0.19	0.4		0.02		
	EU	5	0.19	0.4		0.015	1×10^{12}	
	JP	5		0.4	0.19			25
	China Tier 3	5	4.7			0.4		
	China Tier 4	5	0.19	3.3		0.025	5×10^{12}	
75 ≤ kW < 130	US	5	0.19	0.4		0.02		
	EU	5	0.19	0.4		0.015	1×10^{12}	
	JP	5		0.4	0.19			25
	China Tier 3	5	4.0			0.3		
	China Tier 4	5	0.19	3.3		0.025	5×10^{12}	
130 ≤ kW < 225	US	3.5		0.4	0.19	0.02		
	EU	3.5	0.19	0.4		0.015	1×10^{12}	
	JP	3.5		0.4	0.19			25
	China Tier 3	3.5	4.0			0.2		
	China Tier 4	3.5	0.19	2		0.025	5×10^{12}	
225 ≤ kW < 450	US	3.5		0.4	0.19	0.02		
	EU	3.5	0.19	0.4		0.015	1×10^{12}	
	JP	3.5		0.4	0.19			25
	China Tier 3	3.5	4.0			0.2		
	China Tier 4	3.5	0.19	2		0.025	5×10^{12}	
450 ≤ kW < 560	US	3.5		0.4	0.19	0.02		

	EU	3.5	0.19	0.4		0.015	1×10^{12}	
	JP	3.5		0.4	0.19			25
	China Tier 3	3.5	4.0			0.2		
	CN Tier 4	3.5	0.19	2		0.025		
	US	3.5		0.67	0.19	0.03		
	EU	3.5	0.19	3.5		0.045	-	
kW ≥ 560	JP							
	China Tier 3	3.5	6.4			0.2		
	China Tier 4	3.5	0.4	3.5		0.1	5×10^{12}	

It is observed that emission limits of CO and HC are similar as compared with US Tier-4 and EU Stage V, China's non-road Tier-4 emission limits are still very lenient in PM, NOx, and NHMC emissions as compared with overseas standards. Overall, China non-road Tier-4 standards are considered comparable with US Tier 4 interim and EU stage IV standards. However, the control of nonroad diesel emissions in China is considered to be a very comprehensive and holistic approach according to the government sources.

In order to control black smoke of diesel engines, solid particle number (PN) test requirements are added in China non-road Tier-4 standards. PN value is controlled to be less than $5\text{x}10^{12}$, per kWh, Diesel Particulate Filter (DPF) technologies are usually adopted to control the PN values to meet the requirements.

3. Diesel engine emissions control of non-road mobile machineries

Similar to the EU requirements in Commission Delegated Regulation (EU) 2017/655 for in-service testing, China required the non-road diesel engines with horsepower over 37 KWh be tested using vehicle carried PEMS system during the operations period. Over 90% of the tested results on CO and NOx emissions should have their in-service conformity (ISC) values below 2.5.

GB36866-2018 sets the requirements for testing of smokes from non-road diesel engines (MEE, 2023c). For China non-road Tier-3 or Tier-4 engines, the light absorption coefficient should be measured by opacity meter and get a result of less than 0.5 per meter for engine horsepower more than or equal to 37 KWh, or 0.8 for larger engines. Ringelmann blackness class should not more than 1 for all engine tiers. Visible smokes from any diesel engines are disallowed.

Smoke measurements can be carried out with an opacity meter according to national standard GB 3847-2018 or using the Ringelmann method as described in an appendix to GB 36886-2018.

National technical standard HJ 1014-2020 has included the requirements for the installation of engine telematics and satellite navigation precision positioning systems for non-road mobile machinery equipped with diesel engines of horsepower equal to or above 37kW. All the in-service construction equipment units are required to transmit emissions related data and locations to the centralized management and supervision system operated by MEE according to the specified data types and data format.

Since 2017, 10 ppm diesel, low emission diesel fuel with a sulphur content of less than ten parts per million, has been widely supplied in Chinese market, which can fully meet the requirements of non-road tier-4 diesel engines. Use of biodiesel in non-road engines are not compulsory, but both production, sales, and use of biodiesel can take advantages of government support in the forms of taxes, loans, fundings, et. in green technology support area.

Plagued by serious air pollutions in large cities such as Beijing and Shanghai, more stringent measures have been taken to control the emissions from construction equipment at the municipality level. Beijing implemented non-road Tier-4 standards as early as Dec 2021, Shanghai and Shenzhen implemented in May 2022, all ahead of national commencement time of 1 Dec 2022. Most of the large cities set low-emission zones to prohibit the use and operations of so called yellow-label equipment of high-pollution engines. Video surveillance cameras are also used in some strategic areas to automatically identify and report on smoky vehicles or equipment.

4. Conclusions

Although China lagged behind in setting strict emission criteria for construction equipment, for construction industry which heavily relying on non-road mobile diesel equipment. The new non-road Tier-4 standard implemented in China since Dec 2022 will effectively control and greatly reduce emissions of construction equipment in the world's largest construction market and the largest construction equipment market. A comprehensive and holistic approach has been taken in the emission control of construction equipment in China. Apart from the more stringent emission standards in construction equipment manufacturing, sales, import, and deployment, there are strict registration and administration systems in place to track, control and manage the real time emissions of construction equipment. Vehicle carried PEMS systems are used to measure the emissions of in-service construction equipment. Construction equipment units with black smokes are strictly prohibited through technical measures and management procedures.

Acknowledgements

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References

[1] iimedia Think Tank, "Market development and outlook of global construction equipment," https://data.iimedia.cn/data-classification/theme/44323833.html (Access date: 05.10.2023)
[2] Ministry of Ecology and Environment (MEE) , P.R. China, "Annual Report on China Mobile Source Environmental Management 2022," https://www.mee.gov.cn/hjzl/sthjzk/ydyhjgl/ (Access date: 05.10.2023)
[3] DieselNet, How Emissions Are Regulated," https://dieselnet.com/standards/intro.html (Access date: 05.10.2023)
[4] Ministry of Ecology and Environment (MEE) , P.R. China, "Limits and measurement methods for exhaust pollutants from diesel engines of non-road mobile machinery (CHINA Ⅲ，Ⅳ), GB 20891—2014", effective on 1 Oct 2014, https://www.mee.gov.cn/ywgz/fgbz/bz/bzwb/dqhjbh/dqydywrwpfbz/201405/t20140530_276305.shtml (Access date: 05.10.2023a)
[5] Ministry of Ecology and Environment (MEE) , P.R. China, "Limits and measurement methods for exhaust pollutants from diesel engines of non-road mobile machinery (CHINA Ⅲ，Ⅳ), GB 20891—2014 revisions", https://www.mee.gov.cn/xxgk2018/xxgk/xxgk01/202012/W020201231356400113096.pdf (Access date: 05.10.2023b)
[6] Ministry of Ecology and Environment (MEE) , P.R. China, "Limits and measurement methods for exhaust smoke from non-road mobile machinery equipped with diesel engine, GB36886-2018" , issued on 7 Nov 2018, https://www.mee.gov.cn/ywgz/fgbz/bz/bzwb/dqhjbh/dqydywrwpfbz/201811/t20181113_673591.shtml (Access date: 05.10.2023c)
[7] Ministry of Ecology and Environment (MEE) , P.R. China, "Emissions control technical requirements of non-road diesel mobile machinery, HJ 1014-2020" , effective on 28 Dec 2022, https://www.mee.gov.cn/ywgz/fgbz/bz/bzwb/dqhjbh/dqydywrwpfbz/202012/t20201231_815684.shtml (Access date: 05.10.2023d)

DISEASES IN CONSTRUCTION WORKERS: A CRITICAL REVIEW AND RESEARCH OPPORTUNITIES

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Abstract

There is a need for change in the construction industry to respond to increasing competitive pressure for more productive systems. Thus, given the concern for improving productivity levels in the industry, it is necessary to face the problem from all perspectives. One of these perspectives of analysis is the worker, who plays a key role in the productivity and final results of a project. This is especially relevant in those parts of the world where construction work remains labour-intensive, so occupational and chronic diseases become of interest. Healthier workers are physically and mentally more energetic, robust, productive, and less likely to be absent from work due to illness. Although many employers are now concerned about the health of their workers, their efforts have focused more on medical costs (insurance) than on interventions to understand the impact of health on workforce productivity. Through a systematic literature review, this article describes the status of some occupational and chronic non-communicable diseases in developing countries and how they affect productivity in the construction industry. This will make it possible to have clarity on the diseases that affect construction workers and that have been most studied, such as cardiovascular diseases, chronic respiratory diseases or diabetes, and also to identify diseases whose impact has been little studied and that require further analysis in order to propose concrete actions to deal with them. Thus, cardiovascular diseases, chronic respiratory diseases and diabetes are the most analyzed diseases in the construction sector. However, mental health, musculoskeletal disorders and audiological diseases are also becoming relevant.

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Keywords: cardiovascular diseases, construction workers, diabetes, musculoskeletal diseases, productivity.

1. Introduction

Construction productivity is a significant determinant of success in the projects carried out in the industry [1] since it promotes cost savings and the effective use of resources [2]. There is a need for change in the construction industry to respond to growing competitive pressure for more productive systems, given that the sector presents important problems concerning productivity. Thus, given the concern for improving productivity levels in the industry, it is necessary to address the problem from all perspectives.

One of the most analyzed perspectives is the economic one. In this context, economic losses from occupational accidents in some industrialized countries have been estimated at 3 to 5% of gross domestic product (GDP), with the World Health Organization [3] stating that economic losses (resulting from incapacity for work and early mortality related to exposure to occupational risk factors) can reach 10 to 15% of GDP.

Another approach focuses on the worker, who has a fundamental role in the productivity and results of a project. Occupational diseases are of interest in those parts of the world where construction work remains labour-intensive. According to estimates by the International Labor Organization [4], 5,000 workers die per day from work-related diseases in what are considered occupational accidents, occupational diseases, "work-related diseases", and diseases made worse by work and during 2016, almost 1.9 million people died from work-related diseases and injuries [5].

Healthier workers are physically and mentally more energetic, robust, productive, and less likely to be absent from work due to illness. Although many employers today are concerned about the health of their workers, their efforts have focused more on medical costs (insurance) than on interventions to understand the impact of health on workforce productivity.

Materials, tools, rework, work acceleration, poor coordination, project changes and their management are the main factors that affect productivity [6] and therefore are the most researched topics. The health problem and its impact on productivity differ from the research focus in the construction sector [7].

While it is true that most of the research conducted focuses on cardiovascular diseases [8, 9, 10,11], studies are also beginning to extend to somatic and mental illnesses [12, 13, 14], including acute and chronic pain [15]. The importance of non-immediate consequences to prolonged exposure to noxious agents has also been studied in osteoarticular; musculoskeletal; dermal; respiratory; neuropsychological; otological; or fatigue diseases [16].

Thus, this article analyzes research on some occupational and non-communicable diseases in non-developed countries, aiming to deepen the understanding of how this affect productivity in the construction industry. Through a systematic review using the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) methodology [17], we describe the status of these occupational diseases, compare the data and analyze the effect of these on productivity in the construction industry in undeveloped or developing countries.

2. Method

This review was carried out following the methodology PRISMA checklist 2009 [17]. Publications from 2000 to 2023 indexed in the Google Scholar, Scopus, Scielo and Latindex databases were retrieved using the keywords "diseases", "construction worker", and "list of LATAM country".

The results obtained from these databases were 43. Each of these articles was reviewed by the authors, taking into consideration that each study had to meet the following criteria: (1) analysis in the construction sector, (2) studies on diseases, (3) articles where the study was conducted in Latin America, (4) published between 2000 and 2023, (5) articles written in English, Spanish or Portuguese and (6) articles published in peer-reviewed journals.

In the screening stage, 19 articles were eliminated because they were not related to the construction sector, and in the eligibility stage, seven articles were eliminated because they did not have peer review. Figure 1 shows the PRISMA flow chart, showing that after the entire process, 17 articles were included in the qualitative analysis.

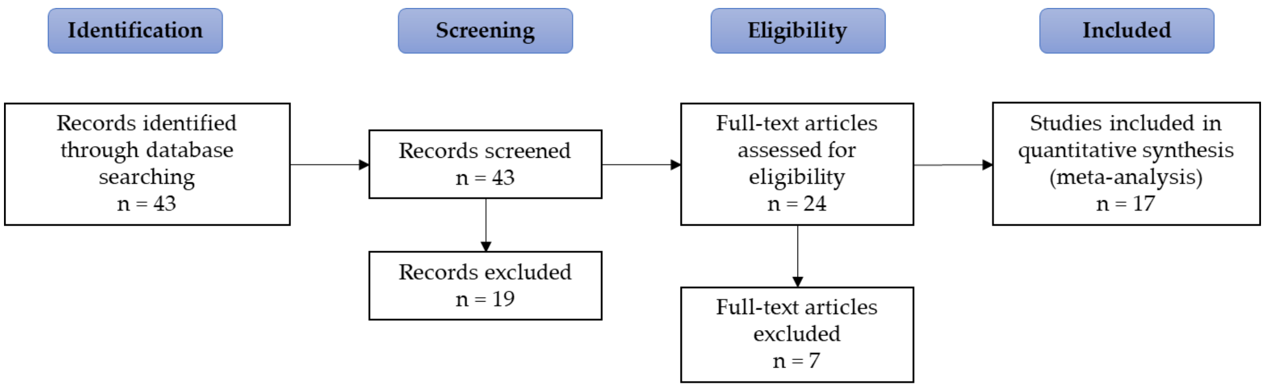

Figure 1. PRISMA Flow diagram of literature search and review. Source: By Authors based on PRISMA 2009 [17].

2.1 Selection of articles based on the selected criteria

Finally, based on the criteria selected for the analysis, the aim is to understand which occupational and non-communicable diseases are analyzed in LATAM and how they affect productivity in the construction industry. The 17 articles included in the analysis, results and discussion are shown in Table 1.

Table 1. Articles retained for analysis

Authors	Year	Country	Sector	Disease
Zarate et al. [18]	2009	Chile	Miners; N= 4673	obesity, diabetes, cardiovascular disease
Salinas et al. [19]	2014	Chile	Construction worker; N=194	obesity
Salinas et al. [20]	2016	Chile	Construction worker; N=142	obesity
Caichac et al. [21]	2013	Chile	Miners; N=94	obesity
Rodríguez [22]	2015	Colombia	Construction worker; N=291	obesity
Rodríguez Nieves et al. [23]	2019	Ecuador	Construction worker N=54	metabolic syndrome
Viana and Carvalho de Oliveira [24]	2017	Brazil	Civil construction; N=50	cardiovascular disease
Martinez and Dias de Oliveira [25]	2006	Brazil	metal and steel company's workers; N= 3777	diabetes
Machado Susseret, Briceno-Ayala and Radon [26]	2019	Argentina	Migrant construction workers N= (134+141)	musculoskeletal
Olivares, Villalobos-Rodríguez and Cerda [27]	2019	Chile	Construction workers; N=186	musculoskeletal
Cabrera Pazmiño and Quinde Alvear [28]	2021	Ecuador	Civil worker; n=4	hearing disease
Loera Gonzaléz et al. [29]	2006	Mexico	Construction worker statistics of occupational diseases and occupational accidents	hearing disease
Ostos [30]	2019	Venezuela	Construction worker n=20	respiratory
Barrios et al. [31]	2023	Chile	Construction worker; N=180	mental health
Da Costa Leao et al. [32]	2018	Brazil	Migrant construction workers N=709	mental health various
Fajardo-Zapata et al. [33]	2009	Colombia	Construction worker; N=1175	various
Silva [34]	2002	Argentina, Brazil, Paraguay & Uruguay	Database	various

3. Analysis

One of the most studied topics has been obesity to understand its prevalence and direct impact on work and cost. Zarate et al. [18], when investigating the cost of health and work absenteeism associated with obesity, found that in the study group, the prevalence of obesity was 28.2%. Therefore, the increase of severe and morbid obesity increases the health cost by 17% and 58%, respectively, regarding absenteeism, subjects with arterial hypertension, diabetes mellitus and dyslipidemia, present on average 17.7, 21.2 and 13.5 days of absenteeism respectively. Salinas et al. [19] shows the prevalence in a group of Chilean workers of overweight (41.8%) and obesity (40.2%). Rodríguez Nieves et al. [23] did something similar with 54 Ecuadorian workers, where 57.4% were overweight and 14.8% obese. In the case of Colombia, Rodriguez [22] showed that of the 291 subjects studied, 46% of workers were overweight and 15% obese. Another study in Brazil of 50 subjects showed that 52% were overweight and 18% obese [24].

Associated with the previous topic, Salinas et al. [20] demonstrated the importance of performing interventions in construction workers. Interventions decreased the metabolic syndrome from 44.4% to 38.3%, associated with a high rate of accidents. Caichac et al. [21], like Salinas [20], evaluated the importance of intervention. Although he did not obtain a significant decrease in the results (a decrease of only 0.4 points), he did show a decrease in systolic blood pressure, glycemia and triglycerides.

Martinez and Días de Oliveira [25] showed that the prevalence of blood pressure was 24.7%, intense work stress, sedentary lifestyle, alcohol consumption, body mass index over 25, altered cholesterol and triglycerides were associated with high blood pressure. On the diabetes mellitus side, the value was 11.5%.

Regarding musculoskeletal diseases, Machado Briceño-Ayala and Radon [26] describe the precarious situation of immigrant workers in Argentina, where 80% of workers reported suffering from low back pain, compared to 42% of local workers. The results show that immigrant workers are more afraid to report poor working conditions or health problems because they fear legal punishment or deportation. Olivares [27], on the other hand, analyzes compliance with the maximum weights allowed by Chilean regulations on construction sites, where it was observed that hand labourers exceed the Recommended Weight Limit by 15.69 kg, bricklayers by 15.17 kg and ironworkers by 10.7 kg, even though the weight handled is under the limit of 25 kg established by Chilean Law 20.949. This article highlights that a technical, administrative, and engineering reflection is required to avoid musculoskeletal problems for workers.

Concerning to hearing diseases, Loera González [29] analyzes hypoacusis as acoustic trauma in occupational diseases in Mexico. In 2000, this disease accounted for 41% of workers' illnesses, where cases resolved by lawsuits increased by 105% in 4 years, and the estimated monthly cost per worker was 277 Mexican pesos. Cabrera Pazmiño and Quinde Alvear [28], on the other hand, upon conducting a field analysis, determined that there is an overexposure and acoustic overdose of workers who handle compaction equipment for long hours and generate a high level of noise, where the health recommendations presented by the WHO are not being complied with since the values exceeded 85dB.

Ostos [30] studied the general knowledge that construction workers have about respiratory diseases. Thirty percent of the respondents do not know the origin of occupational asthma, 60% are not familiar with silicosis, and 65% are not aware of actions to prevent respiratory diseases.

Regarding mental health studies, Barrios et al. [31] analyzed sleep quality and fatigue. The results show that workers are at high risk for other health problems. For example, BMI measures show that many suffer from overweight and obesity. The cognitive-behavioural intervention showed that workers reduced their levels of sleepiness and fatigue.

Da Costa et al. [32], on immigrant workers in Brazil, analyzed the ailments of this group, where the results indicated physical and psychosocial suffering, along with pains in the spine, head, stomach, or throughout the body, in addition to intense effort, fatigue, insecurity in the execution of activities, among others. They also mentioned intimidation, humiliation, lack of respect and homesickness.

In various topics category, the Fajardo – Zapata, Méndez-Casallas and Molina [33] study showed that 34% of the Colombian workers in the construction industry who were studied presented hypoacusis. In contrast, 30% presented some visual refraction defect, 13% had pterigion, 13% had varicose veins, 4% had abdominal wall hernias, 16% were overweight, 4% obesity and 6% had alterations of the spinal column. Meanwhile, 9% of the group evaluated had had occupational accidents.

Finally, Silva [34], comparing the situation of workers in Argentina, Brazil, Paraguay and Uruguay, pointed out that there is sufficient data and a lack of periodic medical examinations in Argentina. Even so, the most frequently identified diseases were respiratory, eye and musculoskeletal diseases. In Brazil, health concerns have been improving, and the list is not only limited to obesity issues but also to hearing loss, dermatosis, repetitive strain injury, ophthalmologic problems, or pneumoconiosis. In Paraguay, it is challenging to evaluate workers because 95% still need a contract. Finally, in Uruguay, the databases are outdated and until 1999, skin diseases, allergies, acoustic trauma and musculoskeletal problems predominated. In general, there needed to be a higher level of control in the countries analyzed in this study.

4. Conclusion

Few studies have been conducted in LATAM on the health of construction workers. The country with the most significant number of studies was Chile, with seven studies focused on obesity or cardiovascular problems. Of the 17 studies analyzed, only one focused on health costs and absenteeism as factors related to productivity. The rest are only descriptive.

Regarding obesity, some LATAM countries share the same rates of obesity and overweight, but some studies highlight the excellent results of early interventions.

There has also been an increase in research on construction work among migrants where precariousness and mental health problems stand out.

In hearing or musculoskeletal diseases, the problem is repeated in the construction sector, where tasks must be performed manually, affecting hearing (compacting machines or cango) or transporting loads musculoskeletal issues.

The results show that there still needs to be more knowledge about how illnesses impact workers' performance and quality of work and personal life. It is necessary to conduct more studies that address these issues to develop actions that help to reduce the prevalence of these diseases and help to form a healthier, motivated and committed workforce.

References

[1] P. Porntheokasemsan and S. Charoenpornpattana. “Identification of factors affecting productivity in Thailand’s construction industry and proposed maturity model for improvement of the productivity”. Journal of Engineering, Design and Technology 17(5), 849-861. 2019, doi.org/10.1108/JEDT-10-2017-0109
[2] B. Sultan and W. Alaghbari. “Priorities for Sustainable Construction Industry Development in Yemen”. International Journal of Applied Engineering Research 12(6), 2017 pp. 886-893. In: https://www.ripublication.com/ijaer17/ijaerv12n6_13.pdf
[3] WHO European Center for Environment and Health. “Guidelines on Quality Management in Multidisciplinary Occupational Health Services”. Copenhagen: WHO Regional Office for Europe, 1999.
[4] International Labour Organization. “Prevention: a global strategy. Promoting Safety and Health at Work”. The ILO Report for World Day for Safety and Health at Work. Geneva: ILO, 2005
[5] World Health Organization and International Labour Organization. “Global Monitoring Report: WHO/ILO Joint Estimates of the work related Burden of disease and injury 2000-2016”. 92pp. 2021. In: https://www.ilo.org/wcmsp5/groups/public/---ed_dialogue/---lab_admin/documents/publication/wcms_819788.pdf
[6] R. Rivas, J. Borcherding, V. González and L.F. Alarcón. “Analysis of factors influencing productivity using craftsmen questionnaires: case study in a Chilean construction company”. Journal of construction engineering and management, 137(4), 312-320. 2011, doi: 10.1061/(ASCE)CO.1943-7862.0000274
[7] G. Philipp. “El trabajo de la carpintería siempre es malo para la salud: Antecedentes y aportes antropológicos al estudio de los procesos de salud-enfermedad de los trabajadores de la construcción”. Revista de la Escuela de Antroplogía, XXIX (145), 1-23, 2021, doi: 10.35305/revistadeantropologia.v0iXXIX.145
[8] S. Leka and A. Jain. “Health impact of psychosocial hazards at work: an overview”. Geneva: WHO, 2010.
[9] J.V. Johnson and E.M. Hall. “Job strain, work place social support, and cardiovascular disease: a cross-sectional study of a random sample of the Swedish working population”. Am J Public Health, 78(10): 1336-42. 1988, doi: 10.2105/AJPH.78.10.1336
[10] J.V. Johnson, W. Stewart, E.M. Hall, P. Fredlund and T. Theorell. “Long-term psychosocial work environment and cardiovascular mortality among Swedish men”. Am J Public Health, 86(3): 324-31. 1996, doi: 10.2105/AJPH.86.3.324
[11] M. Kivimäki, P. Leino-Arjas, R. Luukkonen, H. Riihimäki, J. Vahtera and J. Kirjonen. “Work stress and risk of cardiovascular mortality: prospective cohort study of industrial employees”. BMJ; 325(7369): 857. 2002, doi: 10.1136/bmj.325.7369.857
[12] B. Charbotel, S. Croidieu and autres eight autors. “Working conditions in call-centers, the impact on employee health: a transversal study. Part II”. Int Arch Occup Environ Health, 82(6): 747-56. 2009, doi: 10.1007/s00420-008-0351-z
[13] M. Kivimäki, J. Ferrie, J. Head, M. Shipley, J. Vahtera and G. Marmot. “Organisational justice and change in justice as predictors of employee health: the Whitehall II study”. J Epidemiol Comm Health. 58(11): 931-937. 2004, doi: 10.1136/jech.2003.019026
[14] M. Lohela, C. Björklund, E. Vingård, J. Hagberg and I. Jensen. “Does a change in psychosocial work factors lead to a change in employee health?” J Occup Environ Med, 51(2): 195-203. 2009 In: https://www.jstor.org/stable/45009485
[15] P. Saastamoinen. M. Laaksonen, P. Leino-Arjas and E. Lahelma. “Psychosocial risk factors of pain among employees”. Eur J Pain, 13(1): 102-108. 2010, doi: 10.1016/j.ejpain.2008.03.006
[16] M. Sánchez Aguilar, G. Pérez manriquez, G. gonzález Díaz and I. Peón Escalante. “Enfermedades actuales asociadas a los factores de riesgo laborales de la industria de la construcción en México”. Revista Medicina y Seguridad en el Trabajo, 63 (246). 28-39. 2017
[17] D. Moher, A. Liberati, J. Tetzlaff, and D. Altman. “PRISMA Group. Preferred reporting items for systematic reviews and meta-analyses: The PRISMA Statement”. Ann. Intern. Med. 151, 264–269. 2009, doi: 10.7326/0003-4819-151-4-200908180-00135
[18] A. Zarate, Crestto. M. and autres six autors. “Influence of obesity on health care costs and absenteeism among employees of a mining company”. Rev Méd Chile, 137, 337-344. 2009
[19] J. Salinas, L. Lera, C. González, E. Villalobos and F. Vio. “Feeding habits and lifestyles of male construction workers”. Revista médica de Chile, 142(7), 833-840. 2014, doi: 10.4067/s0034-98872014000700003
[20] J. Salinas, L. Lera, C. González and F. Vio. “Assessment of a nutrition education intervention among construction workers”. Revista medica de Chile, 144(2), 194-201. 2016, doi: 10.4067/s0034-98872016000200008

[21] A. Caichac, F. Mediano, G. Blanco, L. Lera, C. Yañéz, F. Vio and S. Olivares "Food and nutrition intervention for miners with cardiovascular risk factors, based on formative research". Revista Chilena De Nutrición, 40(4), 336-342. 2013, doi: 10.4067/S0717-75182013000400002.

[22] R. Rodríguez. "Variables cardiovasculares en trabajadores de la construcción en Santander (Colombia). Perfil comparativo años 2011 y 2012". Hipertensión y Riesgo vascular, 32(3), 105-112. 2015, doi: 10.1016/j.hipert.2015.01.001

[23] R. Rodríguez Nieves, Torres E. and autres six autors "Prevalencia de síndrome metabólico en trabajadores de una empresa de construcción en Guayaquil, Ecuador". Revista Latinoamericana de Hipertensión, 14(5), 638-643. 2019. In: https://www.redalyc.org/articulo.oa?id=170262877019

[24] T. Viana and M. Carvalho de Oliveira. "Risk factors for the development of coronary artery disease in civil construction professionals". MUNDO DA SAUDE, 41(2), 154-162. 2017

[25] M. Martinez and M. Dias de Oliveira. "Risk Factors for Hypertension and Diabetes Mellitus in Metallurgic and Siderurgic Company's Workers". Arquivos Brasileiros de Cardiologia, 87, 471-479. 2006, doi: 10.1590/S0066-782X2006001700012

[26] N. Machado Susseret, L. Briceno-Ayala and K. Radon. "Prevalence of low back pain in migrant construction workers in Mar del Plata, Argentina". American Journal of Industrial Medicine, 62(9), 777-782. 2019, doi: 10.1002/ajim.23016

[27] G. Olivares, V. Villalobos, Rodríguez C. and E. Cerda. "Difference of Actual Handled Weight and the Recommended Limit for Dynamic Asymmetrical Manual Handling Tasks in Chilean Construction Workers". In Proceedings of the 20th Congress of the International Ergonomics Association (IEA 2018) Volume III: Musculoskeletal Disorders 20 (pp. 561-569). Springer International Publishing. 2019, doi: 10.1007/978-3-319-96083-8_74

[28] C. Cabrera Pazmiño and A. Quinde Alvear. "Evaluation of the Exposure to Noise of Civil Workers When Excavating and Compacting with Pneumatic Equipment in the Sewage Execution Stage: Case study of Cuenca – Ecuador". AIP Conference Proceedings. AIP Publishing LLC, 2022. p. 090009

[29] A. Loera Gonzaléz, S. Salinas-Tovar, G. Aguilar-Madrid, and V. Borja-Aburto. "Hipoacusia por trauma acústico crónico en trabajadores afiliados al IMSS, 1992-2002". Revista Médica del Instituto Mexicano del Seguro Social, 44(6), 497-504. 2006. In https://www.redalyc.org/pdf/4577/457745536002.pdf

[30] J. Ostos. "Information on respiratory disease prevention in construction workers". Revista de Salud VIVE. Revista de Investigación en Salud . 2(4). 17 – 24. 2019, doi: 10.33996/revistavive.v2i4.20

[31] S. Barrios, M. Masalan, X. Ferrada, S. Campos-Romero and Y. Molina. "Sleep Quality and Fatigue in Construction Workers Effect of a Cognitive Behavioral Intervention". Journal of Occupational and Environmental Medicine, 65(3):235-241, 2022, doi: 10.1097/jom.0000000000002716

[32] L. Da Costa Leao, A. Murano, F. Borges and J. Machado. "The health of Haitian immigrant workers in Mato Grosso, Brazil: vulnerabilities and risks", Salud colectiva, 14(4), 779-795. 2018

[33] A. Fajardo-Zapata, F. Méndez-Casallas and L. Molina. "Estado de salud de los trabajadores del sector de la construcción en Bogotá Colombia". Ciencia & Trabajo; 12(38): 210-213. 2009.

[34] M. A. Silva. "Taking risks in order not to loose one's job: the health sequels for construction workers in Mercosur". Sociologias, 358-399. 2002, doi: 10.1590/S1517-45222002000200014

EVALUATION OF WOOD FLY ASH AS A CEMENT REPLACEMENT MATERIAL IN CONCRETE

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Abstract

Biomass is the largest source of renewable energy in the European Union, of which 60% comes directly or indirectly from forests. The most common way of producing energy from biomass is combustion, and this process yields substantial quantity of ash. The cement and concrete industry has been identified as one of the main potentials for biomass ash utilization. This paper presents the results of an experimental study aimed at determining the influence of wood fly ash on the properties of concrete. Wood ash was sampled from three power plants using different technologies of incineration and different types and parts of wood were used as a fuel which consequently had a large impact on the properties of ash. Subsequently, workability, heat of hydration, stiffness development, 28-day compressive strength, apparent porosity, and capillary absorption were determined on concrete mixes prepared with WFA as cement replacement from 5–45% by weight. Cement replacement up to 15% with the finest WFA accelerated hydration, stiffness development, and increased compressive strength of concrete up to 18%, while replacement with coarser WFA's led to a decrease in compressive strength of up to 5% and had more gradual heat liberation. The dominant effect that could explain these findings is attributed to the filler and filling effect mechanisms.

Keywords: biomass; wood fly ash; supplementary cementitious materials

1. Introduction

The need to reduce greenhouse gas emissions accelerates the transition to renewable energy sources. Biomass is the largest source of renewable energy in the European Union (EU), of which 60% comes directly or indirectly from forests [1, 2]. The most common way of producing energy from biomass is combustion, and this process yields on average a quantity of ash between 2.7% and 3.5% of the original weight of wood biomass [3]. It is estimated that in 2018 about 11 million tons of ash were produced in the EU-28 countries, most of which is wood biomass ash (WBA) [4].

During combustion in a biomass plant, two types of ash are generated: bottom ash and fly ash. Ash from the combustion of natural woody biomass contains valuable plant nutrients such as K, P, Mg, and Ca, most of which are contained in the bottom and coarse fly ash, while volatile heavy metals are concentrated in the fine fly ash fraction [5]. Therefore, it has been suggested that the bottom and coarse fly ash fraction should be returned to the forest from which they originated, while the fine fly ash should be utilized in industrial processes or disposed of [5].

The cement and concrete industry has been identified as one of the main potentials for biomass ash utilization [6]. The application of WFA is currently outside the scope of the standard for fly ash for concrete (EN 450-1:2012). Extensive research has been conducted to investigate the possibilities of using WFA as a cement re-placement material [7–16]. It has been reported that WFA from grate combustors and fluidized bed combustors can have hydraulic and/or pozzolanic properties [7, 10, 13]. The utilization of WFA as a cement replacement modifies the workability and mechanical properties of the tested material. As the cement replacement level increases, water demand usually increases and the compressive strength decreases [7–12, 14]. However, replacing cement with WFA can also increase compressive strength when the cement replacement level is low [11, 17]. Improved workability has also been found when WFA was used as a filler and partial replacement for fine aggregate in concrete [13].

Most of the studies on the influence of WFA produced during combustion in biomass plants on the properties of cement composites have been tested on cement pastes and mortars and only a small number of experiments have been scaled up to the concrete level. To develop guidelines for the use of WFA in structural concrete, the interdependence between properties of WFA and the properties of fresh and hardened concrete must be clearly established. The aim of the experimental work presented here is to show the influence of WFA with different physical and chemical properties, used as partial cement replacements, on the properties of fresh and hardened concrete and to identify the most probable mechanisms that govern these changes. The WFA used originates from three different power plants with two types of incineration technologies.

2. Materials and methods

2.1. Characterisation of fly ash and cement

Wood fly ash (WFA) is collected from three powerplants in Croatia. All three plants are co-generation biomass plants producing both heat and electrical energy. Plant F4 is the smallest plant with 1 MW of electrical capacity and 4.1 MW of heat capacity. Wood species mostly used as a fuel are given in Table 1 and the parts of wood used as a fuel consist of wood chips made from roundwood and thinning residues, including twigs, tops, and branches. Plant F5 has a production capacity of 2.75 MW of electrical and 15 MW of heat energy. Plants F4 and F5 use fixed bed combustion in which wood fuel is burned in a grate furnace [18]. Plant F6 is the largest biomass plant with the capacity of production of 8.6 MW of electrical and 16 MW of heat energy. Wood fuel is used in the form of wood chips made from whole trees containing bark, twigs, and leaves. Plant F6 uses a bubbling fluidized bed combustion system with quartz sand as s bed material [18]. The fly ash particles carried from the combustor are captured by bag filters [18].

The information about the incineration temperature of wood biomass is given by the technologists in the power plant. The chemical and physical properties of WFA used in this work are presented in Table 1. The median particle size (d50) is determined from a laser diffraction method using a dry measurement. Elemental composition is determined by X-ray fluorescence according to standard ISO/TS 16996:2015. Loss on ignition (LOI) has been determined according to ASTM D7348-13, density according to ASTM C188-17, and pH value according to EN 12176:2005. More detailed information about fly ash characterisation is presented in [4].

2.2. Concrete mix design and testing methods

WFA was stored in the laboratory for a period of approximately six months before being used in concrete. During storage, WFA was kept sealed in plastic bags and then stored in closed plastic containers. The cement used in this study was Portland cement type CEM I 42.5 R conforming to European standard EN 197-1:2011. The aggregate was crushed dolomite with an average bulk density of 2.8 kg/dm^3 and absorption of 0.47%, 0.66%, and 0.32% for fractions 0/4, 4/8, and 8/16 mm, respectively.

The compositions of the concrete mixes are given in Table 2. Each mix is designated according to the WFA used and the cement replacement percentage. All mixes had the same water/(cement + WFA) ratio of 0.5. A total of 7 concrete mixes containing WFA were prepared with cement replacement percentages of 15% and 30% for ash F4, 15%, 30% and 45% for ash F5, and 5% and 15% for ash F6. In the first stage of the experimental work, a reference concrete mix (M0) and mixes with 15% cement replacement were made. The decision to increase or decrease the cement replacement level in the further mix design process was based on the influence of WFA on the workability of the fresh concrete. Workability was evaluated by the slump test, and cohesiveness was determined by visual inspection of each mix. Before mixing, all constituents were conditioned to a temperature of 20 ± 2°C.

In the fresh concrete consistency by slump test (EN 12350-2:2019), density (EN 12350-6:2019), air content (EN 12350-7:2019), and temperature were measured. The concrete was compacted on a vibrating table. After compaction, the specimens were stored in a room with a temperature of 20 ± 5°C and covered with a plastic sheet. After 24 h, the specimens were demoulded and moved to a curing room where they were cured in the air at a temperature of 20 ± 2°C and a relative humidity of >95%. All measurements were performed on concrete from the same batch.

Table 1. Chemical and physical composition of cement and WFA

	CEM	F4	F5	F6
Combustion technology		GC	GC	BFB
Incineration temperature (°C)	-	700–950	up to 800	up to 850
Wood type		beech, oak, fir, spruce	beech, oak, hornbeam	beech, oak, hornbeam, poplar
P_2O_5	0.22	1.82	1.35	4.03
Na_2O	0.85	0.65	1.32	0.63
K_2O	1.25	6.05	4.77	6.21
CaO	59.80	46.75	16.25	47.35
MgO	2.01	8.26	4.30	4.71
Al_2O_3	4.94	6.16	10.50	3.56
TiO_2	0.23	0.34	1.17	0.25
Fe_2O_3	3.15	2.85	4.23	1.69
SiO_2	21.88	19.80	39.95	14.45
SO_3	3.33	2.73	0.60	3.95
LOI (at 950 °C)	3.60	3.80	8.30	12.70
pH	12.86	13.15	12.97	13.22
d_{50} (μm)	9.4	71.9	120.7	17.8
Density (g/cm^3)	3.10	2.59	2.63	2.33

GC – Grate combustor; BFB – Bubbling fluidized bed

Table 2. Concrete mix composition (quantities per 1 m^3 of concrete).

Mix Designation	M0	F4-15	F4-30	F5-15	F5-30	F5-45	F6-5	F6-15
Cement (kg)	380	323	266	323	266	209	361	323
WFA content (kg)	0	57	114	57	114	171	19	57
Cement + WFA (kg)	380							
w/(cem. + WFA) ratio	0.5							
Water (kg)	190							
Aggregate (kg)	1821	1811	1801	1811	1801	1791	1816	1805
Fine aggregate (kg)	648	645	641	645	641	638	646	643
Coarse aggregate (kg)	1173	1167	1160	1167	1160	1154	1169	1162

The heat of hydration is monitored with the ToniCAL 7336 heat flow differential calorimeter on a cylindrical specimen with a diameter of 150 mm and a height of 300 mm. The rate of heat generation was monitored during the first 5 days of hydration.

Concrete stiffness development was monitored by measuring ultrasonic pulse velocity (UPV) at 1, 2, 7, and 28 days of age using a portable ultrasonic instrument with 54 kHz longitudinal wave transducers. The measurement was performed on concrete cubes with a side length of 150 mm. The same cubes were used for testing the compressive strength of concrete at 28 days of age according to standardized procedure (EN 12390-3:2019).

The capillary absorption measurement was performed on cylinder specimens 150 mm in diameter and height 50 mm, obtained by sawing from the standard cylinder 150 mm in diameter and height 300 mm. Upper and bottom slices of the cylinder were not tested to avoid effects of different boundary conditions. The first 10 mm of side surface in contact with water was coated with epoxy resin. Prior to testing, the specimens were oven-dried at a temperature of 105 ± 5°C until the change in mass for two consecutive weighing became less than 0.5 g (≈0.025% of mass). After cooling to ambient temperature, the specimens were placed in a water container on cylindrical rods, and the water level was adjusted so that the bottom surface of the specimens was immersed in the water 2-5 mm. The mass of the specimens was measured at an interval of 5, 15, 30, 60, 120, 240, and 1500 min. From each mix, three specimens were tested for capillary absorption.

After the capillary absorption test, the water level in a water container was gradually increased at the rate of approximately 1/4 of the height of the specimens per day until the specimens were completely immersed. The specimens were kept under water until the mass of the specimens changed by less than 0.5 g after two consecutive measurements. The specimens were then weighted in surface dry conditions in air and in water. Bulk density in dry ($\rho_{z,dry}$) conditions, apparent solid density (ρ_a), and apparent porosity (p_a) were calculated according to Eqs. (1)-(3). The term apparent is used here because it is assumed that only open pores are filled with water.

$$\rho_{z,dry} = \frac{m_{dry}\rho_w}{m_{sat} - m_{sat,w}}, \tag{1}$$

$$\rho_a = \frac{m_{dry}\rho_w}{m_{dry} - m_{sat,w}}, \tag{2}$$

$$p_a = \frac{m_{sat} - m_{dry}}{m_{sat} - m_{sat,w}} \cdot 100, \tag{3}$$

where m_{dry} is the mass of dry material, m_{sat} is the mass of saturated material, $m_{sat,w}$ is the mass of saturated material weighted in water, and ρ_w is the density of water.

3. Results and Discussion

The fresh concrete density varied between mixes in the range of 2440-2500 kg/m^3. For ashes F4 and F5, the density slightly decreased with increasing WFA content, while for ash F6, the density increased with increasing ash content. This observation on the fresh concrete was confirmed by the results of the bulk density measurements on the hardened concrete (Table 3). The air content was low in all mixtures, indicating dense packing of the concrete constituents after compaction on the vibrating table. The highest air content in mix F6-15 may be partially attributed to the low slump value, which made the compaction of concrete harder. The initial temperature of the concrete varied between 22.2 and 25.1 °C. Only mixes with ash F4 showed a consistent increase in temperature with the increase in ash content. This could be caused by fast initial heat liberation on contact with water but could also be attributed to temperature variations of the concrete constituents prior to mixing.

All mixes had adequate workability to be placed in moulds and compacted on a vibrating table without the loss of homogeneity. The influence of cement replacement on workability, as determined by the slump test, is shown in Table 3. Ash F6 at 15% cement replacement had the largest influence on slump values, where slump decreased from 90 mm measured on the reference concrete to 5 mm. Concrete produced with 15% cement replacement with F4 and F5 ashes showed only minor deviations from the slump value measured on the reference mix. A significant decrease in slump was also present with the F4-30 mix. The cement mix with ash F5 had almost no influence on the slump values. However, mix F5-45 gave a harsh concrete typical for low cement content concrete [21]. This mix also showed increased bleeding and a tendency for the segregation of the largest aggregate particles. It is also interesting to note that the F4-15 and F6-5 mixes showed an increased slump compared to the reference mix. This increase in slump is within the reproducibility limits for the test method (EN 12350-2:2019) but may also reflect the net effect caused by the cement replacement with WFA.

Table 3. Properties of fresh and hardened concrete

Mix Designation	M0	F4-15	F4-30	F5-15	F5-30	F5-45	F6-5	F6-15
Fresh density (kg/m^3)	2470	2470	2460	2470	2450	2440	2480	2500
Temperature (°C)	22.2	23.6	25.1	23.2	23.3	23.3	24.4	22.2
Air content (%)	1.0	0.9	1.1	1.4	0.7	0.3	0.3	1.6
Slump (mm)	90	100	40	85	90	90	110	5
Bulk dry density (kg/m^3)	2371 (±8)	2360 (±16)	2348 (±13)	2363 (±13)	2350 (±15)	2319 (±20)	2373 (±24)	2390 (±8)
Apparent solid density (kg/m^3)	2743 (±4)	2742 (±4)	2718 (±6)	2739 (±22)	2719 (±5)	2713 (±3)	2726 (±8)	2728 (±2)
Apparent porosity (%)	13.57 (±0.17)	13.93 (±0.48)	13.60 (±0.30)	13.73 (±0.21)	13.57 (±0.49)	14.52 (±0.85)	12.94 (±0.64)	12.40 (±0.27)

Numbers in brackets are standard deviations.

SEM images (presented in [4]) show that all the WFAs used in this work contain both irregular and spherical particles and the main difference is in the size of the particles. Compared to the WFA particles, the cement particles seem to be more irregular, which is to be expected since these particles were formed by crushing larger clinker grains. Therefore, replacing cement with WFA increases the “sphericity” of the particles. Another important effect on workability is the water absorbed by the porous particles. The main content of the LOI in fly ash is unburned carbon, which has a high porosity and a very large specific surface and can absorb a significant amount of water [22]. Ash F6 contained particle sizes in a range very similar to Portland cement. The addition of ash F6 to the concrete increases the sphericity of the particles, which, in combination with the small particle sizes improved the packing and enhanced the workability.

Ash F6 also contained the highest amount of unburned carbon (LOI 12.7%), which absorbed a certain quantity of water. The increase in slump in mix F6-5 could be attributed to the enhanced workability due to the filling effect, while at 15% replacement the effect of water absorption and enhanced cohesiveness become dominant. The F4 ash contained coarser particles than the Portland cement, but it also contained 30% of particles <45 μm. This quantity of fine particles together with the increased circularity of the particles enhanced fluidity. At the same time, the portion of particles >45 μm loosens the particle packing, leading to increased water demand. The increase in slump in mix F4-15 could be attributed to the reduced water demand due to the filling effect, while at 30% cement replacement, the loosening of particle packing becomes dominant. Ash F5 contains only 7% of particles <45 μm, so it does not have capability to reduce the water demand through the filling effect. A loose particle packing is created, which decreased the cohesiveness of the mix, while part of the water was probably absorbed by the unburned carbon particles (LOI 8.3%). The existence of optimum WFA content in terms of concrete workability has been observed in [21, 23]

3.1. Heat Generation

Measurements of heat output started 30–90 min after initial contact of cement and water due to the time needed to perform tests on fresh concrete and, if necessary, the additional time required to precondition the specimen so that the concrete temperature is as close as possible to reference temperature of 23°C. All the heat flow curves in Fig. 1 have one significant peak separating the acceleration and deceleration periods of heat release. Replacement of cement with F4 and F5 ashes decreased the peak value of heat flow. Furthermore, the higher the ash content, the larger reduction of heat generation is. At a 15% replacement level, these ashes had almost the same effect on the heat flow. The difference in heat flow between the mixtures with F4 and F5 ashes appeared at a 30% replacement level, and in the mixtures made with F5 ash, there is a larger delay in the peak heat flow and the slope of the curve decreases. Increasing the replacement level to 45% further delayed the hydration process. Effects on heat flow similar to those of ash F5 have been reported for mixtures of Portland cement and type C coal fly ash and have been attributed to the disruption of the aluminate-sulfate balance in mixtures containing >20%

fly ash [24]. Roszczynialski and Nocun-Wczelik [25] also reported that low SO_3 content relative to aluminate content produced a significant peak after 13 h caused by aluminate hydrates. Ash F5 has a significantly higher ratio of Al_2O_3 to SO_3 than cement or both ash F4 and F6 (Table 1), so this could be the main cause of the changes in the course of early hydration in mixtures containing ash F5.

Contrary to mixtures containing ash F4 and F5, mixtures containing ash F6 in both replacement levels had an increased rate of heat liberation compared to the reference mixture. It is well known that even inert mineral admixtures, when blended with cement, can accelerate hydration through filler effect [26]. The increased cohesiveness of the fresh concrete, the reduced porosity (Table 3), and the increased hydration rates found in mixtures with ash F6 (Fig. 1) can all be related to the filler effect.

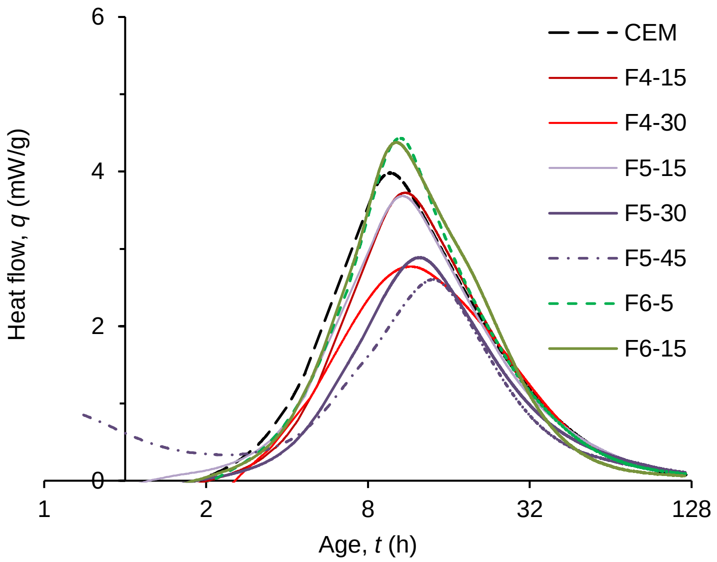

Fig. 1. Heat flow from concrete samples

3.2. Compressive strength

Compressive strength was determined on four specimens from each mix. The average 28-day compressive strength and standard deviation are given in Fig. 2. For both ash F4 and F5, the compressive strength decreased with the increase of ash content in the concrete but for the mixtures with ash F6, the compressive strength increased with the increase of ash content. As already mentioned, the replacement of cement with ash F6 resulted in the densest particle packing which is the main reason for the increase in compressive strength.

The reduction in compressive strength in WFA concrete may also be related to decreased aggregate content and the simultaneous incorporation of ash particles with lower stiffness and strength into the cement matrix. The density of WFA is lower than the density of cement, so the same mass of WFA occupies a larger volume than cement. This results in a reduction in the volume of aggregates in mixtures containing WFA (see Table 2). Since aggregates have greater strength and stiffness than WFA, their replacement by WFA weakens the concrete structure [27]. The decrease in strength may also be related to the lower content of cementitious material when part of the cement is replaced by WFA, as its reactivity is lower than that of the cement.

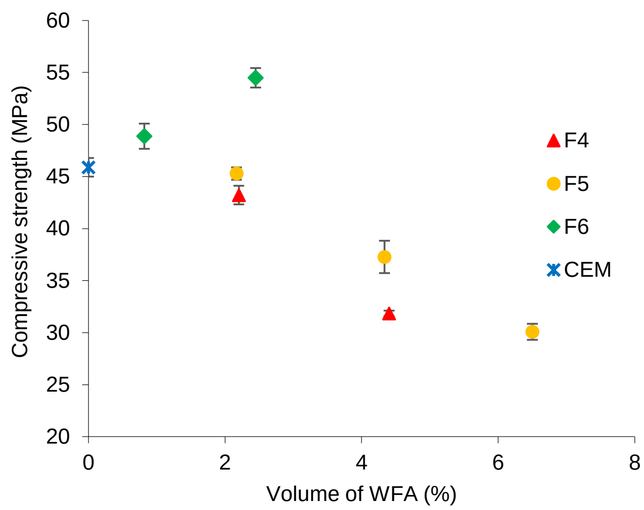

Fig. 2. Compressive strength vs. volume of WFA

3.3. Stiffness development

During the first two days, the mixtures with 15% cement replaced by ash F4 and F5 exhibited slower stiffness development compared to the mixture M0 (Fig. 3). Mixtures containing ash F6 showed an increased rate of heat generation so the accelerated stiffness development can be attributed to an improved hydration process (Fig. 3).

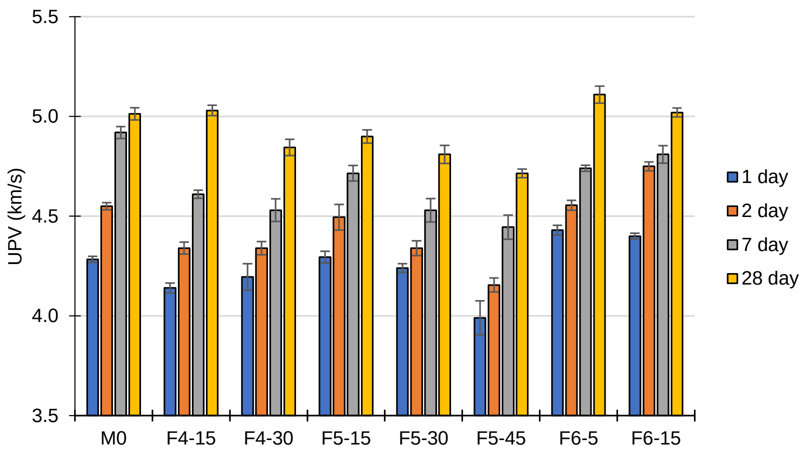

Fig. 3. UPV measured on concrete samples at 1, 2, 7 and 28 days

Mixtures made with ash F4 and F5 exhibited a decrease in heat generation rate so that fewer hydration products were formed within the first days of hydration and the stiffness development is slowed down accordingly. Measurement over the 2–28-day period indicate that the addition of WFA changed the course of stiffness development. In the reference mixture, the period of 2–7 days shows the largest increase in UPV and a very low increase in UPV from 7–28 days. In mixtures with WFA, the increase in UPV is two to five times larger in the period of 7–28 days compared to the reference mixture. This could be due to the reactivity of ash with the species present in the pore solution.

3.4. Capillary absorption

The capillary absorption coefficient for each mixture was calculated and presented in Fig. 4. The capillary absorption coefficient was calculated using the average slope of the water intake curve over the period 120–1500 min. The initial 120 min of measurement was excluded from regression analysis to reduce the impact of nonlinearities contained in the first period of measurement on the value of the coefficient of capillary absorption. The capillary absorption coefficient and its standard deviation show that the replacement of cement with ash F4 and F5 had no significant influence on capillary absorption, regardless of the amount of cement replacement. Only in mixtures made with ash F6 the capillary absorption coefficient was significantly decreased. Like all fluid transport processes through concrete, the rate of sorption is governed by the pore system [28]. Therefore, the reduction in sorption rate can be related to the reduced porosity due to the addition of ash F6.

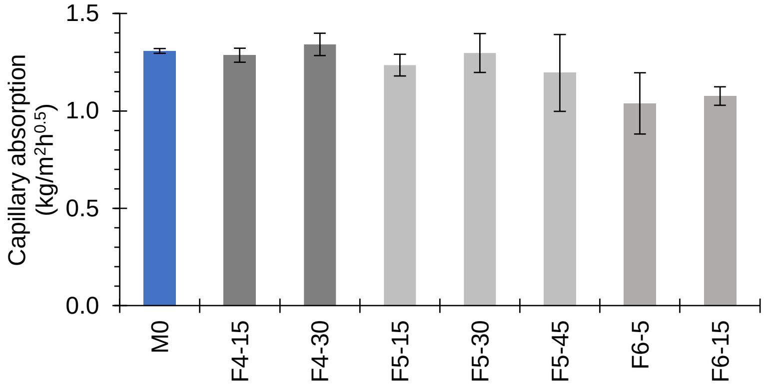

Fig. 4. Capillary absorption coefficients of concrete

4. Conclusions

The incorporation of WFA in concrete as a partial cement replacement can have a large impact on the fresh and hardened concrete properties. Mixtures made with WFA F6 with a particle size distribution close to that of cement exhibited increased cohesivity, which in turn reduced slump and required more energy for compaction of concrete. At the same time, this type of ash accelerated hydration and stiffness development. The increased cohesiveness of the fresh concrete resulted in concrete with a denser structure and lower porosity, which had a positive influence on the compressive strength and permeability. All these effects can be explained by the filler and filling mechanisms. Mixtures made with WFA F4 that had a similar chemical composition to ash F6 but consisted of coarser particles showed no evidence of the filler effect mechanisms. This suggests that governing mechanisms introduced by the cement replacement with fly ash are connected to the physical interactions between the phases.

The water demand of the concrete is balanced by the amount of water adsorbed by the WFA particles and the amount of released entrapped water due to the filling effect. The results obtained on mixtures containing F4 and F6 ashes indicate that there may be an optimum content of WFA at which the water demand could be reduced. Increasing the WFA content beyond the optimum will increase the quantity of water required to achieve targeted workability.

The research presented shows that replacing up to 45% of the cement with WFA has very little effect on capillary absorption and can give concrete with a sufficiently high compressive strength to be suitable for construction purposes.

Acknowledgements

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References

[1] N. Scarlat, J. Dallemand, N. Taylor, and M. Banja, “Brief on Biomass for Energy in the European Union”, J. Sanchez Lopez, and M. Avraamides, Eds.; Publications Office of the European Union: Luxembourg, 2019.
[2] Directorate-General for Energy (European Commission), Navigant. Technical Assistance in Realisation of the 5th Report on Progress of Renewable Energy in the EU. Analysis of Bio-energy Supply and Demand in the EU (Task 3): Final Report; Publications Office of the European Union; Luxembourg, 2020.
[3] S. V. Vassilev, D. Baxter, L. K. Andersen, and C. G. Vassileva, “An overview of the chemical composition of biomass,” Fuel, vol. 89, no. 5, pp. 913–933, May 2010, doi: 10.1016/j.fuel.2009.10.022.
[4] I. Gabrijel, M. Jelčić Rukavina, and N. Štirmer, “Influence of Wood Fly Ash on Concrete Properties through Filling Effect Mechanism,” Materials, vol. 14, no. 23, p. 7164, Nov. 2021, doi: 10.3390/ma14237164.
[5] I. Obernberger, K. Supancic, “Possibilities of Ash Utilisation from Biomass Combustion Plants”, In Proceedings of the 17th European Biomass Conference and Exhibition, Hamburg, Germany, 2009; pp. 2372–2384.
[6] S. V. Vassilev, D. Baxter, L. K. Andersen, and C. G. Vassileva, “An overview of the composition and application of biomass ash.,” Fuel, vol. 105, pp. 19–39, Mar. 2013, doi: 10.1016/j.fuel.2012.10.001.
[7] N. Ukrainczyk, “Reuse of Woody Biomass Ash Waste in Cementitious Materials,” Chemical and Biochemical Engineering Quarterly, vol. 30, no. 2, pp. 137–148, Jul. 2016, doi: 10.15255/cabeq.2015.2231.
[8] S. Wang, A. Miller, E. Llamazos, F. Fonseca, and L. Baxter, “Biomass fly ash in concrete: Mixture proportioning and mechanical properties,” Fuel, vol. 87, no. 3, pp. 365–371, Mar. 2008, doi: 10.1016/j.fuel.2007.05.026.
[9] S. Maschio, G. Tonello, L. Piani, and E. Furlani, “Fly and bottom ashes from biomass combustion as cement replacing components in mortars production: Rheological behaviour of the pastes and materials compression strength,” Chemosphere, vol. 85, no. 4, pp. 666–671, Oct. 2011, doi: 10.1016/j.chemosphere.2011.06.070.
[10] J. Rissanen, K. Ohenoja, P. Kinnunen, and M. Illikainen, “Partial Replacement of Portland-Composite Cement by Fluidized Bed Combustion Fly Ash,” Journal of Materials in Civil Engineering, vol. 29, no. 8, Aug. 2017, doi: 10.1061/(asce)mt.1943-5533.0001899.
[11] I. Carević, A. Baričević, N. Štirmer, and J. Šantek Bajto, “Correlation between physical and chemical properties of wood biomass ash and cement composites performances,” Construction and Building Materials, vol. 256, p. 119450, Sep. 2020, doi: 10.1016/j.conbuildmat.2020.119450.
[12] R. Rajamma, L. Senff, M. Ribeiro, J. Labrincha, R. Ball, G. Allen, V. Ferreira, “Biomass fly ash effect on fresh and hardened state properties of cement based materials,” Composites Part B: Engineering, vol. 77, pp. 1–9, Aug. 2015, doi: 10.1016/j.compositesb.2015.03.019.
[13] M. Berra, T. Mangialardi, and A. E. Paolini, “Reuse of woody biomass fly ash in cement-based materials,” Construction and Building Materials, vol. 76, pp. 286–296, Feb. 2015, doi: 10.1016/j.conbuildmat.2014.11.052.
[14] P.R. Lazik, J. Bošnjak, E. Cetin, A. Kücük, “Application of wood ash as a substitute for fly ash and investigation of concrete properties”, Otto Graf Journal, vol. 19, pp. 103–118., 2020.
[15] S. K. Tulashie, S. Dapaah, D. Mensah, and N. Appiah, “Palm fiber ash as a supplementary cementitious material for the production of mortar prism,” Innovative Infrastructure Solutions, vol. 7, no. 1, Oct. 2021, doi: 10.1007/s41062-021-00602-0.
[16] J. Šantek Bajto, N. Štirmer, S. Cerković, I. Carević, and K. Kostanić Jurić, “Pilot Scale Production of Precast Concrete Elements with Wood Biomass Ash,” Materials, vol. 14, no. 21, p. 6578, Nov. 2021, doi: 10.3390/ma14216578.
[17] R. Kaminskas, V. Cesnauskas, “Influence of activated biomass fly ash on portland cement hydration,” Ceramics Silikaty, vol. 58, pp. 260–268. 2014.
[18] J. Koppejan and S. van Loo, Eds., “The Handbook of Biomass Combustion and Co-firing,” May 2012, doi: 10.4324/9781849773041.
[19] B. Lothenbach, K. Scrivener, and R. D. Hooton, “Supplementary cementitious materials,” Cement and Concrete Research, vol. 41, no. 12, pp. 1244–1256, Dec. 2011, doi: 10.1016/j.cemconres.2010.12.001.
[20] P.K. Mehta, P.J.M. Monteiro, “Concrete Microstructure, Properties, and Materials,” 3rd ed.; The McGraw-Hill Companies: New York, NY, USA, 2006.
[21] Z. Yang, J. Huddleston, and H. Brown, “Effects of Wood Ash on Properties of Concrete and Flowable Fill,” Journal of Materials Science and Chemical Engineering, vol. 04, no. 07, pp. 101–114, 2016, doi: 10.4236/msce.2016.47013.
[22] K. Wesche, Ed., “Fly Ash in Concrete,” Jun. 1991, doi: 10.1201/9781482267051.
[23] G. Skripkiūnas, M. Macijauskas, D. Nagrockienė, and A. Daugėla, “The Influence of Biomass Fly Ash on the Plasticizing Effects in Cement Pastes,” Procedia Engineering, vol. 172, pp. 1015–1022, 2017, doi: 10.1016/j.proeng.2017.02.152.
[24] T. Oey, J. Timmons, P. Stutzman, J.W. Bullard, M. Balonis, M. Bauchy, G. Sant, “An improved basis for characterizing the suitability of fly ash as a cement replacement agent,” Journal of the American Ceramic Society, vol. 100, no. 10, pp. 4785–4800, Jun. 2017, doi: 10.1111/jace.14974.
[25] W. Roszczynialski and W. Nocuń-Wczelik, “Studies of cementitious systems with new generation by-products from fluidised bed combustion,” Journal of Thermal Analysis and Calorimetry, vol. 77, no. 1, pp. 151–158, 2004, doi: 10.1023/b:jtan.0000033198.87490.57.
[26] H. Moosberg-Bustnes, B. Lagerblad, and E. Forssberg, “The function of fillers in concrete,” Materials and Structures, vol. 37, no. 2, pp. 74–81, Mar. 2004, doi: 10.1007/bf02486602.
[27] F. Grau, H. Choo, J. Hu, and J. Jung, “Engineering Behavior and Characteristics of Wood Ash and Sugarcane Bagasse Ash,” Materials, vol. 8, no. 10, pp. 6962–6977, Oct. 2015, doi: 10.3390/ma8105353.
[28] A.M. Neville, Properties of Concrete, Fourth and Final Edition; Pearson Education Limited: Essex, UK, 2004.

PAVEMENT DEFECT CLASSIFICATION AND LOCALIZATION USING WEAKLY SUPERVISED DEEP LEARNING

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Abstract

Automated detection of road defects has historically been challenging for the pavement management industry. As a result, new methods have been developed over the past few years to handle this issue. Most of these methods relied on supervised machine learning techniques, such as object detection and segmentation methods, which need a large, annotated image dataset to train their models. However, annotating pavement defects is difficult and time-consuming due to their ununiformed and complex shapes. To address this challenge, a weakly supervised pavement defect classification and localization framework using deep learning is proposed in this paper. This framework has two steps: (1) a robust hierarchical two-level classifier that classifies the defects in images, and (2) First, defects are primarily localized using a weakly supervised method. Next, the defects are segmented from the localized patches obtained in the previous step. The feature maps extracted from a weakly supervised method (i.e. Class Activation Mapping) based on the results of the first classifiers are used to train a segmentation network once (i.e. U-Net or Mask R-CNN) to localize and segment the defects in the images. Thus, the proposed framework combines the advantages of weakly supervised and supervised methods simultaneously. A dataset from Georgia State in the USA was used in the case study. The proposed framework obtained high precision of 97%, 88%, 92% and 97% for localizing the alligator, block, longitudinal and transverse cracks, respectively.

Keywords: Deep Learning, Weakly Supervised Object Detection, Class Activation Mapping (CAM), Hierarchical Classifier, U-Net, Mask R-CNN

1. Introduction

Accurate and reliable condition assessment is critical for good pavement management, and automation in this area plays a central role in making the overall pavement asset management program (PAMP). Recently, thanks to drastic developments in computer vision and artificial intelligence methods, pavement defect detection is not only automated, but performance of the overall process is also highly improved [1]–[4]. These methods analyse different aspects of defects to determine the cause of deterioration. They analyse huge data emanating from defects. The more adequate data provided about the age, traffic, and other pavement variables the system has, the more reliable prediction it forms.

Pavement defects are the visible part of the degradation of roads and are symptomatic of broader pavement degradation issues. The main causes of pavement degradation are classified into four categories: structural issues (incapacity), non-conformity of materials, environmental (e.g., freeze/thaw cycles), and construction issues (e.g., compaction problems). Determining the root causes of pavement degradation is crucial in determining the appropriate treatments by PAMPs and the engineers using the tools. Therefore, analysing these defects as with respect to shapes, patterns, topology, severity, and quantity makes it possible to deduce their causes. Since the defect localization plays an important role in pavement condition evaluation, a large number of techniques have been developed to detect and localize the defects in recent years [1].

This paper aims to develop a pavement defect classification and localization framework using a weakly supervised deep learning method based on images captured via passive CCD (Charged-coupled device) cameras. The proposed framework also integrates a GIS-based inspection and asset management system called RUBIX, and deep learning classifier and segmentation modules to recognize and localize defects to evaluate the pavement condition.

2. Review of deep learning methods

Most recent defect detection methods used 2D images taken by CCD cameras and detect pavement defects by applying deep learning methods due to their superior performance. Majidifard et al. [5] used YOLO (You Only Look Once) deep learning framework for defect detection. They gathered 2D crack images from Google Street View and trained the YOLO object detection model with this data to detect cracks in images. However, since YOLO did not quantify the cracks' density, they used the U-Net network for segmentation and quantifying defect density. Li et al. [6] proposed a UAV-based crack detection using Faster R-CNN. Gou et al. [7] have developed a neural network based on the Faster-RCNN with improved feature extraction and region proposal. A two-step crack detection and crack severity classification using the Mask R-CNN has also been proposed [8]. In the first step, the Mask R-CNN was used to localize and classify the defect types for linear cracks, such as longitudinal and transverse cracks. In the second step, a combination of image processing techniques was applied to segment the linear defects more precisely and estimate their severities. A patch-based weakly supervised crack segmentation has also been proposed by Dong et al. [9]. It used the image labels instead of polygon annotations to localize defects in the patches. However, it does not provide any information about the crack type.

3. Proposed method

The proposed framework consists of deep learning-based classification and localization modules integrated with a GIS-based inspection and asset management system called RUBIX. The proposed deep learning modules benefit from the advantages of both supervised and weakly supervised methods.

In the classification module, images and extracted patches from localization are classified in terms of defect type and severity, respectively. In defects' localization module, first, feature maps are extracted from the defect type classifier. Then, these feature maps are used as weakly supervised features to localize the defects using Class Activation Mapping (CAM) [10]. Finally, U-Net or Mask R-CNN are used to segment the defects from the CAM method heatmaps as supervised methods; and the segmented patches are sent to the second-level classifier to classify their severities. Hence, this framework combines the advantages of weakly supervised and supervised methods. Fig. 1 shows the block diagram of our proposed method. In this paper, four types of defects (i.e. longitudinal (LON), transverse (TRN), alligator (ALG), and block (BLK) cracks) are localized in pavement images.

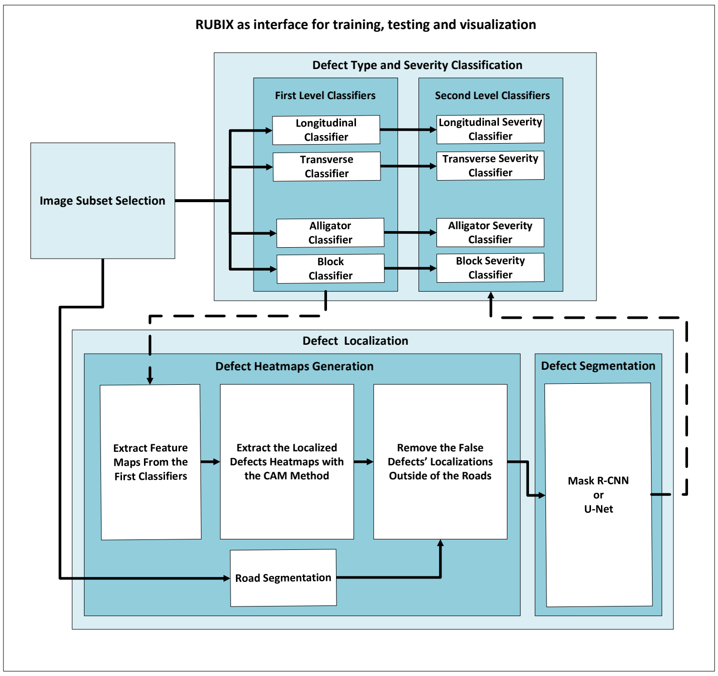


Fig. 1. The proposed method.

3.1. Classification module

In the classification module, the images and their corresponding generated localized patches are passed through two-level consecutive hierarchical classifiers to classify the type and severity of defects using the Residual Neural Network (Resnet101) [11]. It provides a residual network that can be extended to a deeper scale with much more hidden layers without suffering from vanishing gradient and optimization problems. The first-level classifier indicates whether there is a specific type of defect in the image or not. If it classifies the image as an image with a specific defect type, first, the feature maps extracted from the first-level classifiers are used to localize and segment the defect patches. Next, the patches extracted by the localization module will be passed to the second-level classifier to identify the severities of the defects, which play a key role in pavement condition evaluation. In the first-level classifier, each type of defects is classified by its assigned classifier separately. Thus, four classifiers are used to classify the four defect types.

In the second-level classifier, three defect severity levels are defined (i.e. high, medium, and low severity) for each defect. Fig. 2(a), Fig. 2(b) and Fig. 2(c) show high, medium, and low severity defects for each type. Hence, four classifiers specify the severity of the defects for each defect type.

3.2. Localization modules

After identifying the defects and their types by the classifiers, feature maps extracted from the first classifiers are segmented to localize the classified defects using two steps. In the first step, the CAM method is used as a weakly supervised method to localize the defects in heatmaps from the feature maps. In the second step, U-Net or the Mask R-CNN are applied as supervised methods to generate the segmented defect images from the heatmaps.

Fig. 2. Samples of some transverse, longitudinal, alligator and block cracks for three severities.

3.2.1. Generation of defect heatmap

After classifying the defects, the feature maps from the first classifiers of the two-level classifiers are used to localize the defects in the given images using the CAM method. Although the CAM method extracts discriminative features, which occur mostly within the object region, sometimes it highlights other regions outside of the region of interest (ROI), which is the road area. Thus, in order to handle this challenge, road segmentation is used to reduce the false localizations outside the ROI. Another drawback of this method is that it does not detect the whole shapes of objects, especially when the objects are complex, such as pavement defects. This incomplete detection leads to discontinuity in segmented localized images while applying HSV (hue, saturation, value) color space filtering. This problem is less severe for linear defects, such as longitudinal and transverse cracks, but gets worse in the case of area defects, such as alligator and block cracks. As can be seen in Fig. 3, the CAM method fails to extract all parts of defects. Fig. 3(a), Fig. 3(b) and Fig. 3(c) show original images, their corresponding CAM localization results and segmented images for each defect type respectively.

3.2.2. Defect segmentation

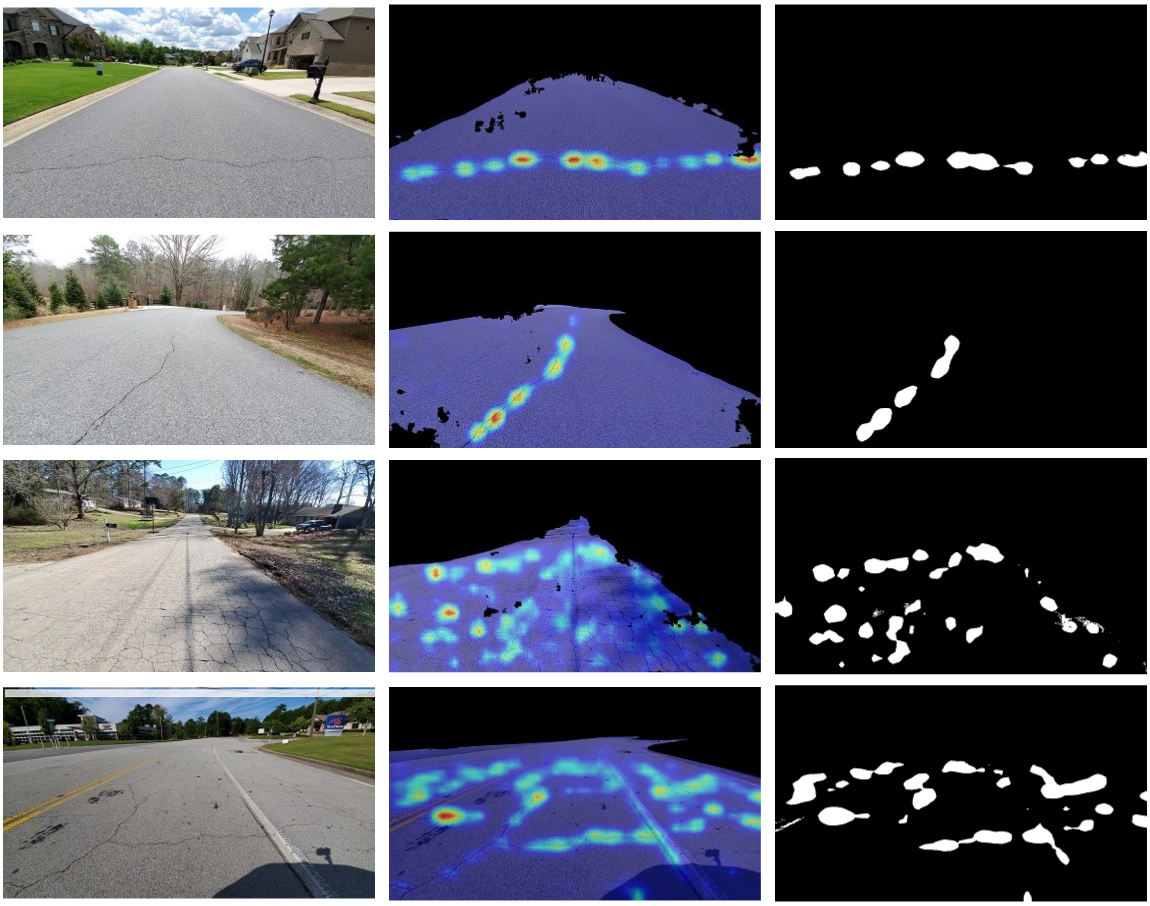
In the Section 3.2.1, it was illustrated that the CAM method segmented images cannot extract all parts of the defects. To address the aforementioned discontinuity problem in the CAM heatmap segmented images, the proposed framework uses U-Net or Mask R-CNN as supervised deep learning segmentation modules to segment the defect more precisely as unified segmented objects from the CAM heatmaps. U-Net is a convolutional neural network that was developed for biomedical image segmentation with a small number of data [12]. In the first part, it extracts the distinguishable and meaningful features from the image; and in the second part, it upsamples the feature maps multiple times to the original size of the image to generate the image segmentation. Mask R-CNN is a region-based convolutional neural network for instance segmentation and object detection that can extract the bounding boxes and the mask segmentations of the objects simultaneously [13]. It uses a lightweight binary classifier as Region Proposal Network (RPN) to generate multiple ROIs to detect and segment objects.

TRN

LON

ALG

BLK



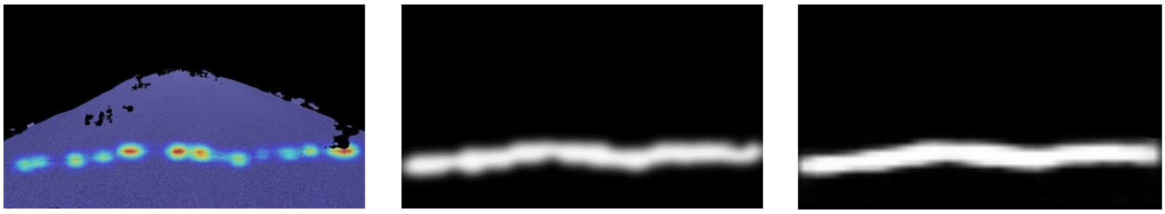
(a) Original image (b) Localized defect image (c) Segmented defect image

Fig. 3. Samples of CAM method localization and segmentation.

Fig. 4 shows a sample of the proposed method in defect localization and segmentation for a transverse crack. Comparing Fig. 4 and the first row of Fig. 3 demonstrates that in contrast to the CAM method segmentation results, the proposed method does not suffer from the discontinuity problem in defect segmentation.

A semi-automated process was used for providing the dataset to train the segmentation modules described in Section 3.2.3.

TRN



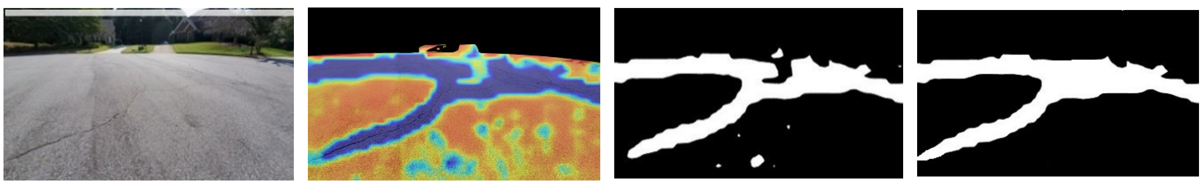
(a) CAM method feature map (b) U-Net Segmentation result (c) Mask R-CNN Segmentation result

Fig. 4. Sample of generating defect segmentation image from the result of CAM heatmap.

3.2.3. Training for defect segmentation

To provide data to train the supervised modules, a semi-automated method is proposed that processes smoothed CAM heatmaps to generate the segmented defect ground truth. Similar to the CAM method, The smoothed CAM method [14] localizes the defects in the images. This method calculates the first principal component of feature maps multiplied by weights instead of using their average sum. It also augments the images and applies the CAM method multiple times to the combined augmented images. This method reduces the noise of localization and centralizes the detector result at the centre of the object [14]. For our application, this method could join the connected defects in the localized image. In other words, the parts of defects disregarded by the CAM method are detected by the smoothed CAM method. First, images are categorized into two groups: images with defects, and images without any defect. Next, the classifiers are trained with these two classes. After that, feature maps from the trained classifier are used with the smoothed CAM method to localize the defects.

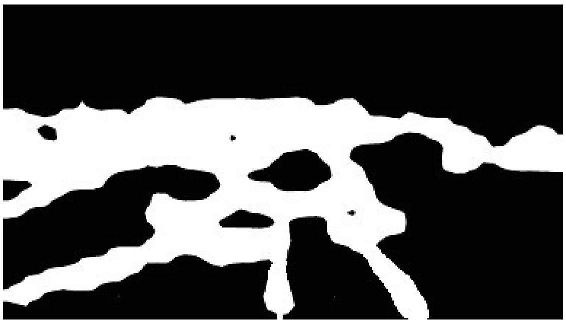
To generate the segmented ground truth images required for the training of segmentation modules, first, 2,000 best smoothed CAM results were selected. Next, HSV filtering was applied to the smoothed CAM method heatmap results. Segmented ground truth images were generated from the smoothed CAM heatmap results by selecting the pixels with values in the HSV range of (0, 0, 100) to (255, 255, 150) (blue areas that contain defects in the localized smoothed CAM images). As can be seen in Fig. 5(b) and Fig. 5(c), the smoothed CAM method has detected all parts of the defects, and its segmentation result does not suffer from the discontinuity that was common in the results of the CAM method. However, it has two drawbacks: (1) the computation time of the smoothed CAM method is six times longer than the regular CAM method (2) its segmentation results are not accurate and need to be cleaned up some parts manually. Thus, finally, the segmented images were manually adjusted to remove false segmented pixels. Fig. 5(d) shows the result of manually modification of the segmented images in Fig. 5(c). These ground truth images and their corresponding CAM heatmap results were used to train U-Net and Mask R-CNN modules. A sample from the generated ground truth and its corresponding CAM heatmap is shown in Fig. 6.



(a) Original image (b) Localized image with smoothed CAM (c) Segmented image by applying HSV filtering (d) Manually modified segmented image

Fig. 5. Generating ground truth from smoothed CAM heatmap result.

(a) CAM method heatmap



(b) Corresponding ground truth

Fig. 6. CAM heatmap sample image and its corresponding generated ground truth to train segmentation modules.

4. Case study

In this section, the proposed framework is evaluated. Images used in the case study were collected from Forsyth County in Georgia, USA, for suburban and country roads. Images were captured with smartphones mounted on the vehicle hood. For all the training stages, the dataset was distributed randomly to roughly 80% for training and 20% for testing. All of the training processes were done in parallel by multiple GPUs.

The Resnet with 101 deep layers (Resnet101) is used as a classifier in the two-level classifier module as explained in the Section 3.1. Binary cross entropy and SoftMax cross entropy are used for the first-level and the second-classifier as loss functions, respectively. Stochastic Gradient Descent (SGD) is used as an optimizer.

In the first-level classifier for each defect, images are categorized into the two groups: the group that includes images with a specific type of defect, and the group of images without that defect, which means it could contain other types of defects. The high accuracy results of the first-level classifier, second-level classifier as well as the total number of images and patches for each defect type are shown in Table 1 and Table 2 respectively. Although all accuracies are high, linear cracks, such as transverse and longitudinal cracks, showed more promising results compared to the area defects, such as block and alligator cracks in the second-level classifier.

Table 1. The experimental results of first-level classifiers.

Defect		With Defect	Without Defect	Overall
TRN	Accuracy	0.98	**0.99**	**0.99**
	Number of images	4,168	5,986	10,154
LON	Accuracy	0.97	0.98	0.98
	Number of images	4,115	6,020	10,135
ALG	Accuracy	**0.99**	**0.99**	**0.99**
	Number of images	3,336	3,877	7,213
BLK	Accuracy	**0.99**	**0.99**	**0.99**
	Number of images	3,331	3,881	7,212

Table 2. The experimental results of second-level classifiers.

Defect		High	Medium	Low	Overall
TRN	Accuracy	**0.98**	**0.98**	**0.98**	**0.98**
	Number of patches	2,815	2,845	2,840	8500
LON	Accuracy	**0.98**	**0.98**	0.97	**0.98**
	Number of patches	2,812	2,816	2,800	8,428
ALG	Accuracy	0.97	0.90	0.92	0.93
	Number of patches	2,710	2,775	2,810	8,295
BLK	Accuracy	0.96	0.96	0.94	0.96
	Number of patches	2,805	2,010	2,700	7,515

To evaluate the proposed defect localization method, 200 images, including four defect types, were annotated with polygon shapes using Rubix. Some annotated samples are shown in Fig. 7. After annotating the images, binary masks were generated from the polygon annotations as ground truth segmentation masks. Next, the masks generated by U-Net and Mask R-CNN (Segmentation module) from the framework were compared with their corresponding ground truth in terms of confidence. Resnet 101 Feature Pyramid Network (FPN) backbone was used as a feature extractor in the Mask R-CNN. Finally, precision, recall and F1-score were calculated.

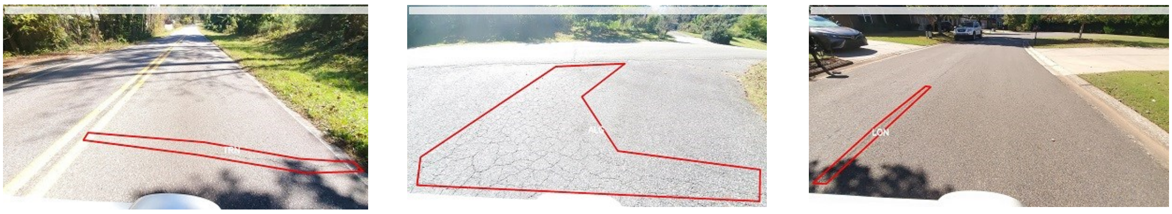


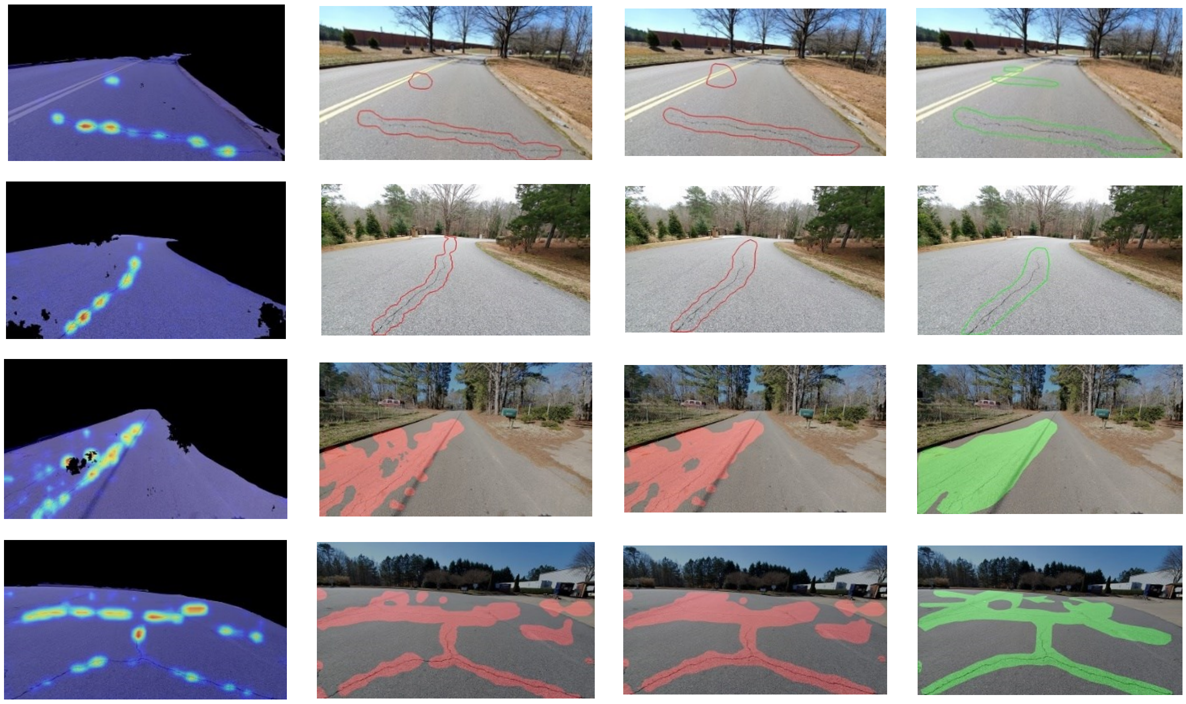
Fig. 7. Samples of annotated images.

Precision refers to the ability of the model to correctly identify true positive cracks from all the predicted positive crack segments. A high precision model will correctly identify most of the true positive crack segments in the image, while also minimizing the number of false positive crack segments. In contrast, recall measures the completeness of true predictions. A model with high recall in pavement crack detection can accurately identify a large proportion of true positive crack segments present in the image, with minimal false negative crack segments. In other words, the higher recall value the model gains, the less missing detected defect it has. This implies that the model can efficiently identify almost all the cracks, regardless of their size and shape, which are present in the image. Thus, to achieve a trade-off between precision and recall, another metric is defined which is F1-score. F1-score is a metric that combines precision and recall. In other words, it can measure the ability of the model to balance between precision and recall. Specifically, it can be regarded as a metric to estimate overall accuracy of the model. The experimental results of the proposed method for each defect type are shown in Table 3.

As can be seen in this table, in terms of precision values, Mask R-CNN and U-Net look the same. However, regarding the recall and F1-score values, Mask R-CNN outperforms U-Net, which means that U-Net has more missing detected defects compared to Mask R-CNN. In contrast, U-Net mean average precision (mAP) values are better than Mask R-CNN, that means regarding all confidences, U-Net shows better precision compared to Mask R-CNN. In general, Mask R-CNN outperforms U-Net in localizing the defects. Additionally, according to the results, substantially, transverse crack showed superior localization results among the all defect types. Fig. 8 shows sample results of the proposed method for localizing defects using the U-Net and Mask R-CNN modules.

Table 3. The proposed method localization experimental results.

Defect	Method	Precision (0.5)	Recall (0.5)	F1 (0.5)	mAP
TRN	Mask R-CNN	0.95	**0.84**	**0.89**	0.81
	U-Net	**0.97**	0.75	0.84	**0.94**
LON	Mask R-CNN	**0.92**	**0.85**	**0.88**	0.73
	U-Net	**0.92**	0.70	0.80	**0.88**
ALG	Mask R-CNN	**0.97**	0.81	**0.88**	0.90
	U-Net	0.95	**0.83**	**0.88**	**0.93**
BLK	Mask R-CNN	**0.88**	**0.85**	**0.86**	0.72
	U-Net	**0.88**	0.79	0.83	**0.83**



(a) CAM heatmap (b) U-Net (c) Mask R-CNN (d) Ground truth

Fig. 8. Defect Localization Results.

5. Conclusions and future work

This paper proposed an end-to-end deep learning method using a GIS-based tool for defect recognition and localization, which could automate the road pavement evaluation process. Since the supervised part of the proposed method needs to be trained only once, the advantage of the proposed method is that there is no need to train its supervised part for new data, which is a time-consuming task in Instance segmentation. Hence the proposed framework could be easily generalized to new data by fine-tuning only the classification part. For training the supervised part a semi-automated process was proposed to generate the ground truth.

The future work is to add more defect types to the classification module, which could lead to a more comprehensive road pavement analysis. In addition, a more precise dataset for training the segmentation part can be provided. In the semi-automated process, smoothed CAM results were used, which contained some parts of the background in addition to defects. Thus, by providing more precise annotations and training the segmentation module with them once, a better localization results can be achieved. Additionally, the Pavement Condition Index (PCI) [15] can be calculated based on the types, severity, and extent of the defects generated by the framework.

References

[1] B. Becerik-Gerber, S. F. Masri, and M. R. Jahanshahi, “An inexpensive vision-based approach for the autonomous detection, localization, and quantification of pavement defects,” No. NCHRP IDEA Project 169. 2015.

[2] K. T. Chang, J. R. Chang, and J. K. Liu, “Detection of Pavement Distresses Using 3D Laser Scanning Technology,” Computing in Civil Engineering (2005), Jun. 2005, doi: 10.1061/40794(179)103.

[3] C. Koch, K. Georgieva, V. Kasireddy, B. Akinci, and P. Fieguth, “A review on computer vision based defect detection and condition assessment of concrete and asphalt civil infrastructure,” Advanced Engineering Informatics, vol. 29, no. 2, pp. 196–210, Apr. 2015, doi: 10.1016/j.aei.2015.01.008.

[4] S. Mathavan, K. Kamal, and M. Rahman, “A Review of Three-Dimensional Imaging Technologies for Pavement Distress Detection and Measurements,” IEEE Transactions on Intelligent Transportation Systems, vol. 16, no. 5, pp. 2353–2362, Oct. 2015, doi: 10.1109/tits.2015.2428655.

[5] H. Majidifard, Y. Adu-Gyamfi, and W. G. Buttlar, “Deep machine learning approach to develop a new asphalt pavement condition index,” Construction and Building Materials, vol. 247, 118513, Jun. 2020, doi: 10.1016/j.conbuildmat.2020.118513.

[6] R. Li, J. Yu, F. Li, R. Yang, Y. Wang, and Z. Peng, “Automatic bridge crack detection using Unmanned aerial vehicle and Faster R-CNN,” Construction and Building Materials, vol. 362, 129659, Jan. 2023, doi: 10.1016/j.conbuildmat.2022.129659.

[7] C. Gou, B. Peng, T. Li, and Z. Gao, “Pavement Crack Detection Based on the Improved Faster-RCNN,” 2019 IEEE 14th International Conference on Intelligent Systems and Knowledge Engineering (ISKE), Nov. 2019, doi: 10.1109/iske47853.2019.9170456.

[8] T. S. Tran, V. P. Tran, H. J. Lee, J. M. Flores, and V. P. Le, “A two-step sequential automated crack detection and severity classification process for asphalt pavements,” International Journal of Pavement Engineering, vol. 23, no. 6, pp. 2019–2033, Oct. 2020, doi: 10.1080/10298436.2020.1836561.

[9] Z. Dong, J. Wang, B. Cui, D. Wang, and X. Wang, “Patch-based weakly supervised semantic segmentation network for crack detection,” Construction and Building Materials, vol. 258, 120291, Oct. 2020, doi: 10.1016/j.conbuildmat.2020.120291.

[10] B. Zhou, A. Khosla, A. Lapedriza, A. Oliva, and A. Torralba, “Learning Deep Features for Discriminative Localization,” 2016 IEEE Conference on Computer Vision and Pattern Recognition (CVPR), Jun. 2016, doi: 10.1109/cvpr.2016.319.

[11] K. He, X. Zhang, S. Ren, and J. Sun, “Deep Residual Learning for Image Recognition,” 2016 IEEE Conference on Computer Vision and Pattern Recognition (CVPR), Jun. 2016, doi: 10.1109/cvpr.2016.90.

[12] O. Ronneberger, P. Fischer, and T. Brox, “U-Net: Convolutional Networks for Biomedical Image Segmentation,” Medical Image Computing and Computer-Assisted Intervention – MICCAI 2015, pp. 234–241, 2015, doi: 10.1007/978-3-319-24574-4_28.

[13] K. He, G. Gkioxari, P. Dollar, and R. Girshick, “Mask R-CNN,” 2017 IEEE International Conference on Computer Vision (ICCV), Oct. 2017, doi: 10.1109/iccv.2017.322.

[14] J. Gildenblat and Contributors, "PyTorch library for CAM methods", 2021. [Online]. Available: https://github.com/jacobgil/pytorch-grad-cam.

[15] “Standard Practice for Roads and Parking Lots Pavement Condition Index Surveys.” ASTM International, 2018. https://www.astm.org/d6433-20.html (accessed Jun. 19, 2022).

VIABILITY OF OFF-GRID CONTAINERIZED REVERSE OSMOSIS WATER TREATMENT IN MAIDUGURI, NIGERIA

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Abstract
This research serves to explore options to provide clean water to communities impacted by water shortages in Maiduguri, Nigeria. This research is meant to provide possible solutions to a water crisis that has mainly been addressed through emergency management. This work explores the viability of solar-powered reverse osmosis water treatment over local boreholes. This required research in several related fields, to include methods of water purification, the application of these methods to borehole water that is pumped to the surface, the viability of solar power as a power option, and the assessment of the water needs and challenges in the area.

The research conducted utilised a mixed method, with both qualitative and quantitative data collection. Technical interviews with water treatment manufacturers and needs assessment interviews with WASH professionals provide qualitative data. NGO-provided multi-sector needs assessment data and water quality results from Maiduguri boreholes will allow for water treatment method development and provide quantitative data.

Needs assessment data and interviews with WASH professionals demonstrated that there is a need for decentralized water treatment with off-grid capability due to energy and water security gaps within the city. Water quality results showed that the level of Total Dissolved Solids (TDS) in untreated water does not necessitate desalinization-style water treatment. Technical interviews with water treatment manufacturers suggested that reverse osmosis is too power intensive and requires more water rejection than ozonation, which is a small-scale water treatment technology that has shown itself to be viable in Nigeria. These results will allow the integration of off-grid water treatment into the medium- and long-term municipal water security planning for Maiduguri. Reverse osmosis remains a viable water treatment process, but ozonation will allow for less power- and water-intensive water treatment.

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Keywords: containerized, Nigeria, off-grid, water, treatment

1. Introduction

There is an active humanitarian crisis in Northeast (NE) Nigeria that has resulted in over 1,500,000 persons being forced to flee their homes due to a violent insurgency[1]. This region of Nigeria, particularly the Borno, Adamawa and Yobe states (BAY states), has long been prone to sanitary water access issues. Compounded with additional stressors of the decade-long conflict, including heightened concentrations of internally displaced persons (IDPs), the water situation has become dire. This research paper will review access to sanitary water in Maiduguri, the largest city in Borno state, and assess the viability of a containerized reverse osmosis water treatment system as a solution to Maiduguri's water crisis. To do this, secondary data from The Sphere Handbook, International Committee of Red Cross, REACH Initiative reports, World Health Organization, and others will be synthesised with primary data from insights from Water Supply, Sanitation and Hygiene (WASH) experts currently working in Borno state.

Findings in this capstone will be qualitative, including semi-structured interviews from several professionals working for the United States Agency for International Development (USAID) and Non-Governmental Organizations (NGOs) with active engagement in Borno State, Nigeria. This capstone also makes mention of data provided by the 2020 Nigeria Multi-Sector Needs Assessment (MSNA), produced by the REACH Initiative, a Geneva-based association that facilitates aid organization planning through the provision of assessment, database and mapping services in humanitarian crises. Lastly, water quality data from the affected region, provided by USAID, shall be reviewed to determine the optimal methods for water treatment.

1.1. *Research Background*

First, clean water in the context of the report must be defined. Aligned with The Sphere Handbook, clean water will be considered as “Water that is palatable and of sufficient quality for drinking and cooking, and for personal and domestic hygiene, without causing a risk to health”[2]. Guidance from The SPHERE Handbook goes on to indicate that water quality testing must meet certain physical, bacteriological, and chemical parameters. Clean, easily accessible, and affordable water is paramount for public health. Due to the topography and weather characteristics in Borno state, Maiduguri is largely served by boreholes which pump water from the ground. Due to this being the prevalent method of water collection, contamination of derived water is the largest risk to public health. Infectious diseases caused by pathogenic bacteria, viruses, and parasites (e.g., protozoa and helminths) are the most common and widespread health risk associated with unclean drinking-water[3].

In Borno State, hand pumping water from a borehole is the predominant method of obtaining water, with over 50% of respondents stating such (Reach Initiative, 2020). These boreholes are a mixture of privately owned shallow boreholes and NGO-funded boreholes in IDP camps. With the prevalence of boreholes, any methods to improve water quality and access will have a large and immediate impact in the area.

Earlier in 2021, the International Committee of Red Cross (ICRC) published a document detailing the short-, medium-, and long-term strategies for clean water in Maiduguri, Nigeria. “in urban areas[in Maiduguri], the ICRC will work in close cooperation with the Ministry of Water Resources (MoWR) to a) implement middle to large-size infrastructure project b) focus on building the capacity of the water authorities to manage their utilities efficiently and c) advocate for the support in the long term of development actors to the MoWR”[4]. These strategies are summarized as the following:

Short-term: The MoWR adopts a clear vision about access to safe drinking water according to national/international standards for Maiduguri urban area, is able to commit to and develop a way forward to reach that vision; The MoWR can stabilize its shrinking daily water production capacity and can avoid a further worsening of the current critical situation in regard to health, household economy and protection.

Medium-term: The MoWR has reached a good working knowledge about its existing water infrastructures, its exact capacity and its condition; the MoWR is able to define the required infrastructural, institutional and financial needs to meet the water demand of the Maiduguri using qualified assumptions for all aspects of the future urban growth of the coming decades.

Long-term: The MoWR, has the capacity, tools and resources to sustainably manage a functioning and adequately sized centralized water supply system for Maiduguri.

This vision was crafted as a shift to proactively managing water resources in Maiduguri, so any future engagements with clean water supply need to conform to these objectives.

Every year, NE Nigeria, including the city of Maiduguri, experiences heavy rains during the three-to-four-month period of the rainy season. During these heavy rains, minor to moderate flooding is common when open drainage systems are quickly overwhelmed by the volume of water that needs to be directed away. In addition, drains are often diminished and clogged from unsecured sediment, trash, and waste. This flooding can also overflow local boreholes, creating points of water contamination. As the city floods, surface water is also contaminated with human and animal waste from nearby pit latrines. This finding lends credence to the need for borehole water treatment, even when the water quality, when tested, does not show evidence of bacteria or organic contamination.

2. Literature Review

2.1. *Introduction*

This literature review will describe the concept and application of reverse osmosis water treatment, it will explore other measures taken to provide clean water to Maiduguri, and it will cover water security impacts in remote and austere regions. This section will also explore some alternative water treatments used in remote areas.

2.2. *Other Methods of Water Purification*

2.2.1. *Electrolysis*

Electrolysis functions by using electricity to split water molecules into corresponding hydrogen and oxygen molecules. This process allows sediment to fall out and disrupts microorganisms present in the charged solution. Ghernaout found that “a lot of studies concern electrolysis which generates a variety of oxidants in the presence of molecular oxygen, including hydrogen peroxide and ozone, as well as free chlorine and chlorine dioxide when chloride ions are present in the solution depending both on the electrode material and applied voltage and the chemical composition (i.e., chloride content) of the water/wastewater” [5]. The author goes on to discuss the dependence of oxidant generation and microorganism killing efficiency, but he does not further explore the application of electrochemical water treatment in small scale applications. The process can be enhanced by coupling with UV activation. Electrolysis aims to generate sulfites, as sulfite activation removes micropollutants and pathogens in its presence. Ultraviolet light at certain lengths can act as a catalyst for the recombination of sulfites and free oxygen molecules generated through electrolysis. Chen discusses the process as follows: “the obvious advantages of the electro/UV/sulfite process are that 1), it avoids the use of toxic peroxymonosulfate/persulfate compounds; 2), sulfite has short residency upon exposure to the air, and produces benign sulfate anion; and 3), it does not affect the overall water quality especially the DO and pH post treatment” [6].

2.2.2. *Ultrafiltration*

Ultrafiltration is a pressure-driven process by which contaminants and heavy metals are removed via a series of increasingly fine filter media. This method is often paired with other water treatment methods, such as reverse osmosis, as a method of removing contaminants without the introduction of chemicals. “Conventional media filtration systems are based on deep bed filtration process while the UF operates on the surface or cake filtration principle…UF is capable of replacing the whole conventional potable water treatment process of sedimentation and media filtration system due to its ability to remove colloid, particles, bacteria and viruses from water.” [7] This process suffers from the constant monitoring required to prevent membrane fouling, which requires reversing flow with permeate periodically. This limits practical application of the solution. Deriszadeh states “Lower surfactant concentrations could, therefore, be employed leading to lower fouling and back contamination and higher permeate flux.” [8].

2.2.3. *Ultraviolet Light*

Ultraviolet light (UV) water treatment functions by passing water over a light bulb emitting UV-C light. This irreparably damages microorganisms DNA, rendering them inert and safe for drinking in water. This form of water treatment does not remove any organic or inorganic pollutants from the water, limiting its use. Timmerman discussed the use of UV light water treatment as a lightweight system, adding “UV light has a bacteriostatic effect, it is not primarily bactericidal…the water treated with [the mobile lightweight system] is disinfected but not sterile” [9]. This form of water treatment has gained prevalence as technology has progressed, allowing the commercial availability of UV-Light Emitting Diodes (LEDs). Wuertele stated “In addition to diversity in wavelengths, UV-LEDs possess several unique advantages such as environmental friendliness (no mercury), compactness and robustness (more durable), faster start-up time (no warm-up time), potentially less energy consumption, longer lifetime, and the ability to turn on and off with high frequency" [10]. Both Timmerman and Wuertele discussed UV disinfection at various wavelengths, but they did not elaborate on how water disinfection is only one part of the required steps for water treatment, depending on the quality of water being tested. UV-LEDs possess another role in water treatment, as it can be used as a catalyst for Advanced Oxidation Processes (AOPs) in the production of Reactive Oxygen Species (ROS). ROS, such as hydroxyls, superoxides, and ozone, serve to decompose contaminants in untreated water. Wang discusses UV role in this phenomenon, stating that "O3 has the disadvantages of low solubility, poor stability and selective reaction with organic pollutant in water, the contaminants often cannot be completely removed in many [cases]. This is why catalysts or other substances (ultraviolet (UV), etc.) are usually added in the process of ozonation for synergistic catalysis to improve the oxidation efficiency" [11].

2.2.4. *Electrodialysis*

Electrodialysis functions similarly to electrolysis; however, instead of a reaction chamber with oxidation occurring, there are charged membranes used to remove unwanted contaminants. Gabarron describes the process succinctly: "The electrodialysis process uses a driving force of direct current power to transfer ionic species from the source water through cation and anion exchange membranes to a concentrate waste stream, creating a more diluted product water stream." [12]. This makes electrodialysis similar to reverse osmosis, in that it is a membrane-driven process, requiring monitoring and reverse flow at times to prevent fouling of the membranes.

2.2.5. *Ozonation*

Ozonation is the process of oxidation of water to remove and mitigate heavy metals such as iron and manganese, salts such as hydrogen sulfide, and microorganisms from water. This process has been demonstrated effective under laboratory conditions, and small-scale decentralized water treatment is being explored as well. Kaspersyk-Hordern describes the process well: "Catalytic ozonation can be considered firstly as homogeneous catalytic ozonation, which is based on ozone activation by metal ions present in aqueous solution, and secondly as heterogeneous catalytic ozonation in the presence of metal oxides or metals/metal oxides on supports. Catalytic ozonation was found to be effective for the removal of several organic compounds from drinking water and wastewater" [13].

Square1 Technologies is a proponent of this water treatment method. The pre-packaged water treatment units combine filtration, ozonation, and UV disinfection to treat water with little wastewater generation, high levels of disinfection, and low power requirements for off-grid usage.

3. **Research Methodology**

3.1. *Research Methodology*

The research required for this body of work will be mixed methods research, consisting of both qualitative and quantitative data. Qualitative data will be gathered by conducting long form interviews with various professionals that work in the WASH sector from USAID and various NGOs that are involved in clean water initiatives. The long form interviews will explore the following base questions:

1. Are there water security issues in Maiduguri, Borno State, Nigeria?
2. Does the local community have access to clean water?
3. How can clean water access be improved for the local population?
4. Are off-grid solutions viable in the Sahel environment experienced in the locale?
5. What water treatment system is most appropriate for the water quality found in the area?

Ideally, these discussions will shed light on previous solutions that may have been implemented, regional challenges that were not uncovered during literature review, and the viability of this solution as a medium-term objective, still fitting in with the Local Government water security goals for the region.

Quantitative data will be comprised of water quality test results and regional weather data. Water quality results will be used to determine the exact style of water purification that will allow the end product to meet WHO clean water guidelines.

Long-form interviews with various professionals involved in funding WASH efforts, both in Nigeria and elsewhere, will make up the qualitative data presented in this paper. The purpose of these interviews will be to both validate quantitative data collected during research and to further refine implementation ideas for the system.

The implementation sequence for this mixed method research shall be considered a Sequential Transformative approach. In other words, the water quality data and water availability data in various communities will form a basis for discussions with professionals in the related fields. Qualitative information will be prioritized, as quantitative data can present an incomplete picture of the difficulties of implementing a new water filtration system in the area. Both results together will be used to explore the practical implementation of the theory of off-grid water filtration. Results will be integrated in the conclusion chapter with further interpretation of both quantitative and qualitative data sources. For example, if the quantitative data points towards electrodialysis or simple UV disinfection over reverse osmosis, and the interviews also suggest that reverse osmosis is too water intensive for the Sahel region, then the conclusion will discuss how both data sources did not indicate that reverse osmosis is the most appropriate solution.

Research strategies involve archival research of other water purification methods and a case study strategy. In this case study, the phenomenon of clean water access will be investigated within the context of borehole usage in Maiduguri, Nigeria. Due to the nature of the case study, multiple data sources will be used to triangulate and ensure that the data points towards an appropriate solution.

This time horizon shall be considered cross-sectional over longitudinal. The period of data collection occurred from 2021-2022, and the viability of the solution is designed for a mid-term solution, designed to last until the Nigerian MoWR has established central water distribution to all affected populations. The core of the research lies in data collection and analysis. Quantitative data will be collected from international organization observations of local population needs. Similarly, water quality results obtained from international organization observations will be used to determine the most appropriate means of water treatment. Qualitative data will be derived from long form interviews with WASH professionals in Maiduguri and Abuja, Nigeria.

4. **Results and Discussion**

4.1. *Interview Design*

As part of the qualitative interview process, the respondents were asked to address the following questions:

1. Could you please tell me your name and current position and share a brief professional background?
2. Could you tell me about clean water access in Borno state?
3. What do you think are the top three challenges for IDPs and host communities in Borno state related to Water, Sanitation and Hygiene?”
4. How can access to clean water specifically in Maiduguri, Nigeria be improved?
5. What other interventions have been implemented? Did it work? What do you think is the best way forward?

6. Are there any projects providing containerized water treatment for boreholes?

After conducting five (5) interviews, the participants provided feedback on the specific wording of questions 3,4,5, and 6. This led to a slight revision of the questions for the remaining three (3) interviews conducted during the study, and the addition of a closing question. The revised questions are as follows:

3. How can access to clean water in Maiduguri, Nigeria be improved?
4. What other interventions have been implemented? Did it work? What do you think is the best way forward?
5. Are there any projects providing containerized water treatment for boreholes?
6. What water treatment solution is most appropriate for the water found in the area?
7. Any other colleagues or contacts that you might recommend that I also interview?

Question 3 was formed in such a way that it could lead to different discussions than those that this paper discusses, so it was removed. Question 6 was then added to receive practical field input on the methods of water treatment already occurring in the area, as this feedback could potentially increase or decrease the viability of reverse osmosis, the method studied thus far.

4.2. *Qualitative Content Analysis*

4.2.1. *Clean Water Access in Borno State*

Surface water contamination was raised as an issue across multiple interviews. Due to the topography and presence of livestock in Borno state, untreated surface water may be contaminated with livestock fecal matter or other organic contaminants. With a lack of water testing, there is an increased risk of a health crisis. Any implemented water treatment system should include regular, scheduled water testing to ensure that contaminants found in the water are being effectively mitigated.

4.2.2. *Other Implementations for Water Security*

Over half of the respondents mentioned some form of operations and maintenance (O&M) training, maintenance activities, and lifecycle delivery of equipment and solutions. All too often humanitarian efforts fall short of lifecycle equipment training. This, combined with scarcity of essential resources (water in this case), leads to equipment needing simple maintenance or repair falling into disrepair and being abandoned in place. To prevent this from occurring, any solution for water treatment should take the following factors into consideration: it must have a set lifecycle established, the required salts and chemicals needed for treatment must be locally available, and the local operator should collect remittance to cover the cost of equipment operation.

4.2.3. *How Can Clean Water Access be Improved?*

The interviews resulted in various views regarding the improvement of water access. Enhanced coordination between state, regional, and local government entities held a common theme in responses. If a containerized water treatment solution were to be proposed, the concept would require buy-in from Nigerian government authorities as well as aid organizations. The issue of drilling excessive boreholes was also brought up. Multiple respondents indicated that excessive boreholes in Maiduguri have caused the shallower ones to dry up. Depending on the soil conditions in Maiduguri, a seasonal aquafer is normal. When there are too many boreholes dug in close proximity, this aquafer drops and can even dry completely. There may be much deeper aquafers present that yield water all year round, and any future boreholes should involve a centralized investigation. This expands the scope of the solution to be implemented. To install viable containerized water treatment plants, hydrogeological studies should be conducted, reviewed and compared to determine the appropriate depth for boreholes in the area.

4.2.4. *Existing Containerized Water Treatment Solutions*

Based on the responses from those interviewed, containerized water treatment is not currently a widely used water treatment modality in the region. This is likely due to several factors: NGO and local government partners have been focused on disaster response to the extent that water quality is unfortunately secondary to the presence of water at all. One of the respondents discussed how thirst-related mortality was a huge concern in the region (Standifer, 2021). Several of the boreholes in the area are also unregistered, meaning that no studies were done beforehand for the viability of year-round water access, proximity to other boreholes and possible sources of contamination, such as a pit latrine nearby, and no water testing is done to ensure that the water is not contaminated and is safe for consumption.

Dr. Jolicouer, a Senior WASH Advisor working with USAID in Maiduguri shed light on the topic of methods of water filtration. “Reverse osmosis water filtration is best for water with high amounts of solutes, such as removing salt from brackish water. Reverse osmosis may be more than what is really needed given the water quality in Maiduguri”.

4.3. *Water quality Data Discussion*

The International Organization for Migration (IOM) conducts water quality testing for boreholes in the Maiduguri LGA. During this research, attempts were made to retrieve water quality data for untested water in boreholes in Maiduguri. This data would allow conclusions to be made regarding appropriate water treatment types, how water quality varies in the region, and current procedures for water treatment. Unfortunately, the data collected does not reveal the raw water characteristics, as it has been treated and chlorinated. This does provide merit, however, in that it reveals that current water filtration methods are limited to inline chlorination. Once this was discovered, further research was conducted to locate water quality results for untreated borehole water in the region.

S/N	PARAMETER	WHO STANDARDS
1	Ammonia	0-1.0mg/L
2	Fluoride	0-1.5mg/L
3	Manganese	0-0.1mg/L
4	Nitrite	0-0.5mg/L
5	Nitrate	0-15mg/L
6	Iron	0-0.3mg/L
7	FRC	0.3-0.5mg/L
8	PH	6.5-8.5
9	Turbidity	<5 NTU
10	Arsenic	0-10mg/L
11	Conductivity	0-1,500uS/cm
12	NO of Coliform	0

Figure 4: Parameters as compared to WHO Water Standards

							WHO	
S/N	Parameter	Gwange	Mashamari	Hausari	Moduganari	Bulabullin Ngarannam	Highest Desirable Level	Maximum Permissible Level
1	Temperature at Time of Analysis (C)	26.6	27.5	29.2	28.3	30	-	40
2	Colour (TCU)	Not Determined	Not Determined	Not Determined	Not Determined	Not Determined	6	
3	Turbidity (NTU)	0.77	0.85	0.78	0.85	0.98	5	5
4	Ph	6.04	6.5	5.72	6.28	6.6	7.0-8.5	6.5-9.2
5	Total Dissolved Solid (mg/L) (TDS)	374	332	547	94	247	500	1500
6	Conductivity (us/cm)	747	664	1092	189	496	NS	
7	Total Alkalinity (mg/L)	60	100	60	60	100	80	120
8	Iron (mg/L)	0	0	0	0	0	-	-
9	Chromium (mg/L)	0	0	0	0	0	-	-
10	Nitrite (mg/L)	0	0	0	0	0	-	-
11	Copper (mg/L)	0.11	0.32	0.47	0.05	0.09	-	-
12	Fluoride (mg/L)	0.33	0.15	0.63	0.92	0.13	-	-

Figure 5: Water Quality Data from five (5) boreholes in Maiduguri, Isa et al, 2012

Figure 5 shows the water quality data collected from a previous study executed in Maiduguri in 2012. When compared to WHO standards, two (2) of the five sampled boreholes fall outside of the standard for pH. Also, the Total Dissolved Solid (TDS) for one (1) borehole exceeds the WHO standards as well. The TDS has an impact on the perceived taste of the water due to suspended salts and heavy metals. Most importantly, the TDS measured from all five (5) boreholes reveal that the water accessed is not brackish. These findings drive equipment selection when it comes to filtration, membranes, and treatment method. Brackish water typically contains 1,000-10,000 mg/L in TDS, and only one (1) borehole exceeded the WHO standard of 500mg/L.

4.4. *Distances Travelled to Collect Water*

	% of Households having access to an improved water source										
	Response Options	Total Number of Households	Bottled	Handpump Borehole	Piped Connection to House	Protected Well	Public Tap	Rain Water	Surface Water	Unprotected Well	Water Seller
LGA Borno	Maiduguri	199	0%	53%	0%	2%	25%	0%	1%	0%	18%

Figure 6: % of households with access to improved water sources, courtesy of REACH, 2020

In 2020, REACH conducted a Multi-Sector Needs Assessment covering topics such as education, health, nutrition, and WASH. In this survey, data was gathered and made available for both Government and Non-government sources to review. In the table above, respondents were asked how water was provided in their household. 53% responded by stating that they accessed boreholes regularly. This represents a significant opportunity for containerized water treatment, as borehole usage is widespread and accepted.

The REACH data is informative for two (2) main reasons: it informs the reviewer of the main method of water collection in the region (boreholes), and it quantifies the distances travelled to collect water for local households. From this needs assessment, we can see that 53% of households in Maiduguri rely on water from boreholes for sustenance. Also worth highlighting is that only 25% are able to rely on public tap water. This points to the impact of water treatment for boreholes, and it points to the current limitations of Maiduguri's water distribution network to supply water to all inhabitants.

5. Conclusions and Recommendations

5.1. *Introduction*

Chapter 4 established an untapped need for off-grid containerized water treatment. As the interviews were conducted and discussions recorded, it became apparent that a decentralized, scalable system, able to be quickly deployed and relocated, provided a definite advantage to the impacted community. Quantitative research shows that the water accessed in the first aquifer is of insufficient quality for drinking water. It also revealed that water quality could vary quite a bit even in the Maiduguri Local Government Area. The qualitative research revealed that there are multiple aquifers in the region that are viable for boreholes, with the second aquifer being higher quality water, less affected by the seasonal water table.

5.2. *Viability of Reverse Osmosis Water Filtration*

The technical interviews that took place during this research revealed that reverse osmosis is viable, as the technology is used in the region frequently. However, combinations of ozonation and UV treatment proves to be just as effective as reverse osmosis in reaching clean drinking water standards with lower energy requirements and less wastewater as a result of the treatment. The standard reverse osmosis system has a waste water ratio of up to 4:1, meaning that for every one (1) gallon of clean drinking water produced, four (4) gallons of unsuitable wastewater is also produced. With Ozonation, this waste water ratio can be drastically reduced. Additionally, Reverse Osmosis can be a power-intensive process, which makes it less suitable for off-grid operation. While off-grid reverse osmosis solutions exist, they do require skilled labor with reverse osmosis filter membrane maintenance concerns, which do not exist in Ozonation. Rather, there are catalysts that are consumed throughout the process that will require replacement after some time, without the constant monitoring requirement.

5.3. *Viability of Off-grid Water Filtration*

Solar power remains the most viable and economically feasible method of off-grid power generation for Maiduguri. The city, which is located in the Sahel region, experiences sufficient solar irradiation for continuous water pumping and purification for up to six (6) hours without the need for an additional battery bank during the dry season. Unfortunately, solar power will be of limited use during the two-to-three month rainy season that occurs, leaving overcast clouds, greatly limiting the efficiency of the panels.

5.4. *Limitations of this Research*

This body of work explores the viability of off-grid reverse osmosis water treatment, and while arriving at a conclusion, more work is required to adapt a commercially viable solution in the market. This research was limited to solar and solar-hybrid solutions for off-grid usage. Other means of off-grid power generation are available and may be viable in the region, but this line of research extends beyond this body of work. This research was also limited to the conditions that are found in Maiduguri, Borno State, Nigeria.

There were some added variables that may have impacted the direction and outcome of the research conducted. When conducting data analysis, two (2) technical interviews were conducted. Both interviewers belonged to Square1 Technologies, an emerging business looking to expand their own ozonation water treatment products in Nigeria. In order to remain impartial, technical interviews from all of the other established and emerging technologies should have been conducted as well. Also, due to the limited research window, only eight (8) qualitative interviews with WASH professionals were conducted. None of the interviews conducted involved local Rural Water Supply and Sanitation Agency (RUWASSA) administrators, who are responsible for the existing water supply network in Maiduguri.

5.5. *Recommendations for Future Research*

The continuation of this research would explore a life cycle cost analysis of ozonation in combination with UV treatment in Maiduguri, with considerations for initial equipment deployment funding, operating expenses, the commercial viability of the system in the environment, and methods to change public perception of treated water.

References

[1] J. Kurtzer, *Out of Sight: Northeast Nigeria's Humanitarian Crisis*. Rowman & Littlefield Publishers, 2020. [Online]. Available: https://www.csis.org/analysis/out-sight-northeast-nigerias-humanitarian-crisis

[2] sphere S. I. Handbook, "Sphere Standards Interactive Handbook - Companion standards(MERS,MISMA,CPMS,CAMP,HIS,LEGS,INEE)." https://handbook.spherestandards.org/ (accessed May 12, 2023).

[3] World Health Organization, "Guidelines for drinking-water quality," 2011, Accessed: May 12, 2023. [Online]. Available: https://apps.who.int/iris/handle/10665/44584

[4] R. Behnisch, "URBAN WATER - VISION: SUPPORT TO THE MINISTRY OF WATER RESOURCES OF BORNO STATE TO STRENGTHENING MAIDUGURI PUBLIC WATER SUPPLY SERVICE," Feb. 2021.

[5] D. Ghernaout, M. W. Naceur, and A. Aouabed, "On the dependence of chlorine by-products generated species formation of the electrode material and applied charge during electrochemical water treatment," *Desalination*, vol. 270, no. 1, pp. 9–22, Apr. 2011, doi: 10.1016/j.desal.2011.01.010.

[6] L. Chen, Y. Xue, T. Luo, F. Wu, and A. N. Alshawabkeh, "Electrolysis-assisted UV/sulfite oxidation for water treatment with automatic adjustments of solution pH and dissolved oxygen," *Chem. Eng. J.*, vol. 403, p. 126278, Jan. 2021, doi: 10.1016/j.cej.2020.126278.

[7] C. M. Chew, M. K. Aroua, M. A. Hussain, and W. M. Z. W. Ismail, "Evaluation of ultrafiltration and conventional water treatment systems for sustainable development: an industrial scale case study," *J. Clean. Prod.*, vol. 112, pp. 3152–3163, Jan. 2016, doi: 10.1016/j.jclepro.2015.10.037.

[8] A. Deriszadeh, M. M. Husein, and T. G. Harding, "Produced Water Treatment by Micellar-Enhanced Ultrafiltration," *Environ. Sci. Technol.*, vol. 44, no. 5, pp. 1767–1772, Mar. 2010, doi: 10.1021/es902862j.

[9] L. F. Timmermann, K. Ritter, D. Hillebrandt, and T. Küpper, "Drinking water treatment with ultraviolet light for travelers – Evaluation of a mobile lightweight system," *Travel Med. Infect. Dis.*, vol. 13, no. 6, pp. 466–474, Nov. 2015, doi: 10.1016/j.tmaid.2015.10.005.

[10] M. A. Würtele *et al.*, "Application of GaN-based ultraviolet-C light emitting diodes – UV LEDs – for water disinfection," *Water Res.*, vol. 45, no. 3, pp. 1481–1489, Jan. 2011, doi: 10.1016/j.watres.2010.11.015.

[11] J. Wang *et al.*, "A new UV source activates ozone for water treatment: Wavelength-dependent ultraviolet light-emitting diode (UV-LED)," *Sep. Purif. Technol.*, vol. 280, p. 119934, Jan. 2022, doi: 10.1016/j.seppur.2021.119934.

[12] S. Gabarrón, W. Gernjak, F. Valero, A. Barceló, M. Petrovic, and I. Rodríguez-Roda, "Evaluation of emerging contaminants in a drinking water treatment plant using electrodialysis reversal technology," *J. Hazard. Mater.*, vol. 309, pp. 192–201, May 2016, doi: 10.1016/j.jhazmat.2016.02.015.

[13] B. Kasprzyk-Hordern, M. Ziółek, and J. Nawrocki, "Catalytic ozonation and methods of enhancing molecular ozone reactions in water treatment," *Appl. Catal. B Environ.*, vol. 46, no. 4, pp. 639–669, Dec. 2003, doi: 10.1016/S0926-3373(03)00326-6.

ASSESSMENT OF OVERHEATING RISK IN FREE-RUNNING RESIDENTIAL BUILDINGS IN PALESTINE UNDER FUTURE CLIMATE

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Abstract

This paper addresses the impact of climate change on residential buildings in Palestine, which recently faced an increased risk of overheating. The study investigates the effect of the thermal properties of the building envelope of a single detached house on increasing the building's resilience to climate change. The overheating risk is evaluated using ASHRAE 55 standard under typical historical and future years (2035, 2065, and 2090) based on RCP-4.5 and RCP-8.5 emission scenarios in three climate zones in Palestine (2A,3A and 2B based on ASHRAE 169-2020). The simulation results reveal that the Medium Energy Efficient Building (MEEB) is more effective in enhancing the thermal comfort of the building compared to the Low Energy Efficient Building (LEEB). However, the risk of overheating increases in future climates, particularly in vulnerable populations and specific locations in the hot, dry zones, such as 2B. This necessitates the implementation of combined mitigation strategies, including both active and passive cooling strategies, highlighting the importance of improving the building's indoor environment and envelope. The findings emphasize the need to incorporate the impact of climate change into building design to ensure energy efficiency, thermal comfort and promote climate-resilient buildings.

Keywords: building performance, climate change, MEEB, overheating risk, Palestine.

1. Introduction

Climate change has already caused widespread impacts and losses worldwide, leading to more frequent and intense extreme weather events. According to the recent IPCC 6th report, global warming is expected to continue, with a high probability of exceeding a 1.5°C increase during the 21st century, which would make it harder to limit warming below 2°C under higher emissions scenarios [1]. These changes contribute to the occurrence of compound heatwaves, which are projected to become more frequent and have long-term impacts. These impacts adversely affect people's health and well-being [1], [2], [3]. Additionally, rising temperatures have resulted in increased mortality rates [4], [5]. The heat-health problem varies from country to country, and countries like Palestine lack mortality data for individual cities or provinces, especially for reasons of climate-related mortality. This underscores the urgent need to conduct studies on climate change to aid in adapting to the changing climate [5]. Extreme heatwaves have a significant impact on the energy performance and indoor thermal conditions of buildings, making it crucial to estimate the risk of overheating in buildings worldwide, as in the case of Gaza, a large sample of residential buildings has been assessed; the study examined the overheating risk in residential buildings using simulations [6]. Such studies are important for understanding how heatwaves affect thermal comfort, as people spend a significant amount of time indoors, ranging between 65-90% [7].

The Eastern Mediterranean region, including the Middle East and North Africa (MENA) region, is a climate change hotspot, experiencing faster warming than other areas [8]. A recent study's findings showed that Palestine has an annual mortality rate of 43 heat-related deaths [9]. The study also predicted an increase in mortality by the end of the century due to a combination of climate change and high population growth. Therefore, efficient mitigation strategies are required [9]. Palestine, along with its neighbouring countries in the Mediterranean region, has experienced extreme weather and faces challenges in achieving sustainability due to its vulnerability to climate change, lack of natural resources, and high energy prices. Among all sectors, the building sector is the most challenging in terms of sustainability [10]. Using appropriate materials in the building envelope is crucial to enhancing the thermal efficiency of climate-resilient buildings in Palestine [11].

Efforts to improve building efficiency are crucial in mitigating their contribution to global warming. Achieving high energy building efficiency (HEEB) in residential buildings involves implementing various strategies, including insulation, smart HVAC systems, and renewable energy technologies [12]. Monna et al. research has focused on evaluating the impact of climate change on building energy performance, drawing on the latest IPCC scenarios and findings from the AR6 report. Some studies have emphasized the importance of assessing building energy performance and its influence on indoor thermal comfort in Palestine [13]. Additionally, other studies have highlighted the significance of considering different insulation materials and thicknesses, as well as investigating the performance of lightweight but insulated walls under diverse climatic conditions in Palestine [14].

This study aims to evaluate the risk of overheating in residential buildings using a whole-building simulation model for historical and future weather data with two levels of thermal properties of the building envelope, referred to as Medium Energy Efficient Buildings (MEEB) and Low Energy Efficient Buildings (LEEB), in three climate zones in Palestine.

2. Methodology

2.1. Building geometry

A single-detached house with two floors, 40% of window-to-wall ratio and 197m^2 of total floor area is selected for evaluating the impact of climate change on indoor overheating, Tis building represents a typical Palestinian construction style [3] consist of stone, concrete, and hollow concrete blocks exterior wall and a concrete flat roof/floor.

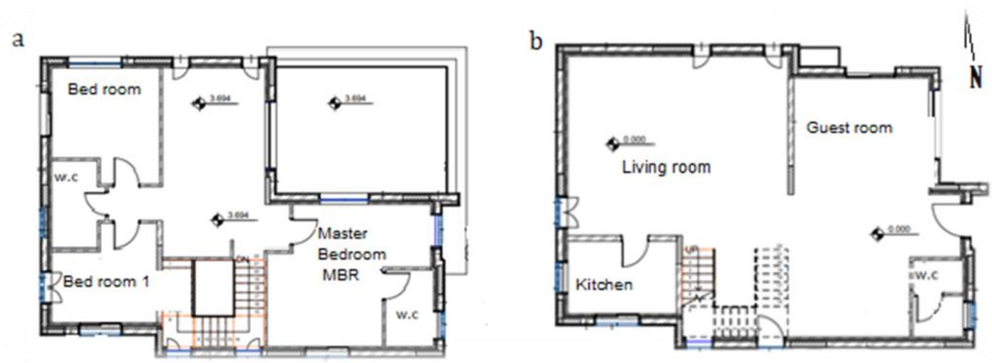

Fig. 1. (a) first floor; (b) ground floor

2.1.1. Building envelope

The following are the scenarios of the existing residential building case study that were chosen:

- Scenario 1 (S1) low energy efficiency building – LEEB: The building without insulation.
- Scenario 2 (S2) Medium energy efficiency building- MEEB: The thermal properties represent the typical building with additional changes in the building envelope.

The details of the building envelope assemblies are shown in Table 1, which illustrates the overall thermal transmittance of the building envelope for the master bedroom (MBR) with an area of 17.36m^2.

Table 1. Overall thermal transmittance of building envelope assemblies- MBR.

Item	Layers- S1, Zone: MBR	LEEB U ($W/m^2.K$)	Layers- S2 Zone: MBR	MEEB U ($W/m^2.K$)
Exterior wall	Limestone 40mm Mortar 30mm Hollow-block 200mm Plaster 20mm	2.4	Limestone 40 mm Mortar 30 mm Hollow block 200 mm Foam Polyurethane 60mm Hollow block 100 mm Plaster 20 mm	0.40
Ground floor	Concrete 250mm Sand 70mm Mortar 30mm Ceramic10mm	2.4	Concrete 250mm Polystyrene90mm Sand 70mm Mortar 30mm Ceramic10mm	0.40
Flat Roof	Bitumen 5mm Sand concrete for roof 70mm Reinforced concrete 250mm	2.0	Bitumen 5mm Sand concrete for roof 70mm Reinforced concrete 250mm Foam Polyurethane90mm	0.27
Window	Single glass	5.8 SHGC 0.75	Double glass, air 13mm	1.6 SHGC 0.55

2.1.2. Settings for whole building simulation- Overheating risk

The building relies on natural ventilation to remove the excessive heat by opening 50% of the windows area when the indoor temperature is higher than 23 °C and the indoor temperature is higher than the outdoor temperature. Also, the interior shading (blind roll) is used to reduce the possible solar heat gain during the day. Simulations were conducted for the hottest room, which is the master bedroom (MBR).

2.2. Thermal comfort criteria

To evaluate the risk of overheating in naturally conditioned spaces, the temperature ranges for operative conditions are evaluated following ASHRAE 55-2017 [15]. The maximum acceptable operative temperature is determined by Equation 1. If Equation 2 yields an operative temperature higher than the upper limit temperature, it indicates the occurrence of overheating. The Upper 80% acceptable limit:

$$T_{c,up} = 21.3 + 0.31 * T_{om} \quad (1)$$

$$T_o = (T_d + T_{mrt})/2 \quad (2)$$

The overheating risk for the two cases (S1 and S2) was analysed and simulated using historical year (TMY data 1961-1990). The formulas were used for the analysis: T_{om} is the monthly mean outdoor air dry-bulb temperature (°C), T_o is the operative temperature (°C), T_d is the indoor air dry-bulb temperature (°C), and T_{mrt} is the mean radiant temperature of the zone (°C).

2.3. Future weather data

Currently, WeatherShift™ [16] is one of the weather morphing tools available to researchers, it is widely used by researchers studying buildings' energy performance [17]. WeatherShift™ used to generate future years 2035 (2026-2045), 2065 (2056-2075), and 2090 (2080-2099) based on the Representative Concentration Pathways (RCP) scenarios (RCP 4.5 and 8.5) that were defined in the IPCC Assessment Report 5 (AR5) and utilized to simulate meteorological variables for the years. The RCP 8.5 scenario assumes the highest levels of temperature and CO_2 emissions by the end of the 21st century, as it remains unclear whether carbon dioxide emissions will decrease or not in the future [18], [19].

2.4. Simulation scenarios

Three different climatic zones in Palestine were chosen for the historical and future assessment of overheating risk on residential buildings, which are: Qalqilya (2A-hot and humid), Jerusalem (zone 3A - warm and humid), and Jericho (hot and dry- for zone 2B), as specified in the ASHRAE climatic data [20] that corresponds to the ARIJ data zones (Qalqilya - Zone 5, Jerusalem - Zone 3, Jericho - Zone 1) [21]. Historical simulations were conducted for all three zones based on and the two building scenarios (S1 - LEEB, S2 - MEEB). Similarly, for future simulations, evaluations were based on the ASHRAE 55 standard and future weather data projections using RCP-4.5 and RCP-8.5 emission scenarios for the years 2035, 2065, and 2090, assuming a 50% median warming scenario.

A total of 24 cases are modelled using DesignBuilder tool for three locations in Palestine and two scenarios condition.

3. Results and Discussion

3.1. Overheating risk evaluation under historical simulation

Fig. 2 shows a comparison of the overheating hours between the LEEB and MEEB scenarios in three locations (Jerusalem, Qalqilya, and Jericho) for historical evaluation. Results show that buildings with low thermal properties of the building envelope (LEEB) experience significantly higher overheating hours compared to buildings with high thermal properties of the building envelope (MEEB), with a difference of 50–100% depending on the building's location. The overheating hours in a building located in cold cities (Jerusalem and Qalqilya) were about 526 hours and 765 hours, respectively, which represent 15% and 23% of the summer period from May 1st to September 30th. However, Jericho Zone had the worst scenario among the three locations, with overheating hours representing 88% (3150 hr) of the summer period. By improving the thermal properties of the building envelope, the overheating hours were reduced from 526 hr to 0 hr in Jerusalem, to 56 hr in Qalqilya, and to 48% (1718 hr) in Jericho. These results are consistent with the results of the sensitivity analysis conducted by Baba et al. [22].

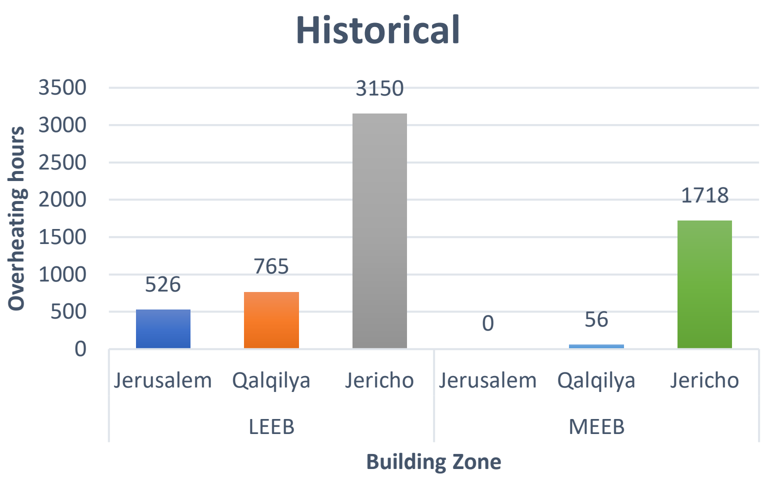

Fig. 2. Overheating hours for LEEB and MEEB under historical simulation

3.2. Overheating risk evaluation under future climate simulation

Fig. 3 presents the effect of climate change on the MEEB building in three different locations. Simulations are conducted under the RCP 4.5 and 8.5 emission scenarios for short-term (2035), mid-term (2065), and long-term (2090) future years.

Under 2035- RCP 4.5 scenario, the overheating hours in Jerusalem and Qalqilya are slightly increased, where the MEEB building would perform better than the LEEB building for the same locations, as the historical simulations had already proved the overheating risk. However, in Jericho, the number of overheating hours may increase by up to 66% (2408 hrs). The results show the number of overheating hours is significantly increased under the RCP 8.5 scenario for the three locations, with the highest probable occurrence of overheating in Jericho at 70% (2515 hrs) compared to RCP-4.5.

Under the mid-term evaluations representing the year 2065, the number of overheating hours may keep increasing under both RCP 4.5 and 8.5 scenarios, highlighting the best case in Jerusalem and the worst case in Jericho, where the overheating hours may represent 87% (3163 hrs) of the summertime. By 2090, the number of overheating hours may increase up to 77% (2786 hrs) of summertime under the RCP 4.5 scenario, and the percentage of 100% overheating occurrence may be recorded for (3612 hrs) under the worst scenario of RCP 8.5 for MEEB building. Under future climates, some chosen designs that have natural ventilation and interior shading may be insufficient to mitigate the risks of overheating.

The study's results highlight the urgent need for appropriate mitigation measures in building designs, as they play a crucial role in enhancing the performance of residential buildings in Palestine and promoting sustainable building practices. To counter the increasing trend of overheating and reduce overheating hours during intense heatwaves, a combination of passive and active cooling strategies should be considered. The study indicates that the current condition of Low Energy Efficient Buildings (LEEB) is insufficient, while the Medium Energy Efficient Building (MEEB) case needs further development, especially in zones like Jericho. Considering the impacts of climate change and overheating in building design is vital as a proactive measure. Evaluating the overheating risk of existing buildings and implementing effective strategies can mitigate risks and ensure a safe and comfortable indoor environment, thus promoting the construction of climate-resilient buildings.

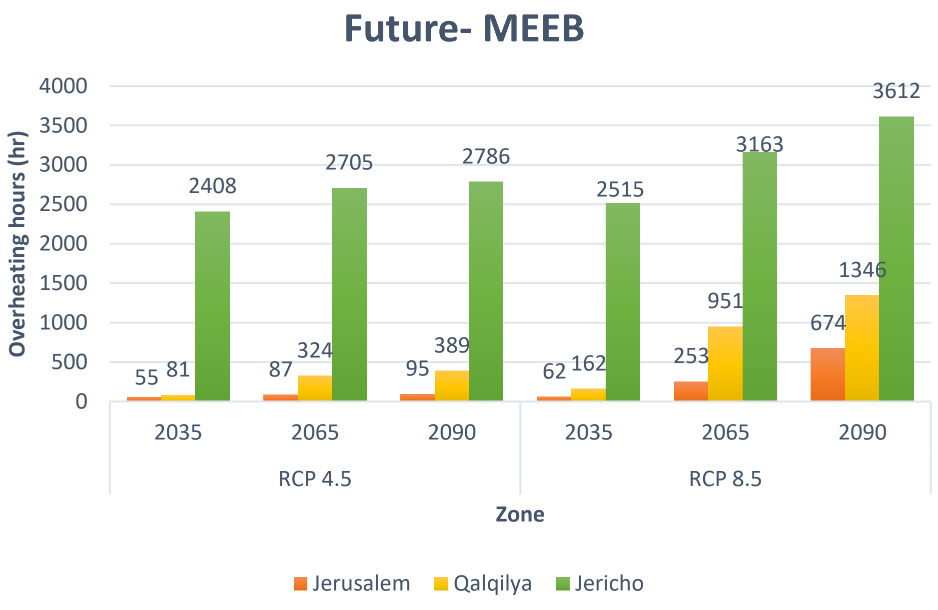

Fig. 3. Overheating hours in MEEB buildings under future climate

4. Conclusions

This paper evaluates the overheating risk in residential buildings in Palestine, considering the effect of thermal properties of the building envelope, i.e., medium energy efficient buildings (MEEB) and low energy efficient buildings (LEEB). The assessment also includes the effect of climate change on the indoor thermal condition under historical and future years in three Palestinian climate zones, i.e. Qalqilya, Jerusalem, and Jericho. Future weather data are generated based on the RCP 4.5 and RCP 8.5 emission scenarios for the years 2035, 2065, and 2090. The study utilises the Designbuilder simulation tool to conduct whole-building simulations and analyze the overheating risk.

The results indicate that MEEB buildings demonstrate greater adaptability to overheating risks compared to LEEB buildings. The proposed MEEB buildings type proved to be climate-resilient and more efficient in addressing overheating concerns in Qalqilya and Jerusalem during the selected summer period. Overall, different climate zones in Palestine are susceptible to overheating, and the MEEB building type is particularly effective in addressing this issue in Jerusalem and Qalqilya. However, additional mitigation measures such as exterior shading and efficient cooling systems are necessary for regions like Jericho, where the risk of overheating is more severe. It is recommended to employ a combination of passive and active cooling strategies to mitigate these risks. In conclusion, the study emphasizes the importance of considering the impacts of climate change on building design and performance. It underscores the need to evaluate the overheating risk in existing buildings and develop strategies to mitigate it, ensuring a safe and comfortable indoor environment while promoting the construction of climate-resilient buildings.

References

[1] "The IPCC Sixth Assessment Report on Climate Change Impacts," Population and Development Review, vol. 48, no. 2, pp. 629–633, Jun. 2022, doi: 10.1111/padr.12497
[2] E. L. Lawrance, R. Thompson, J. Newberry Le Vay, L. Page, and N. Jennings, "The Impact of Climate Change on Mental Health and Emotional Wellbeing: A Narrative Review of Current Evidence, and its Implications," International Review of Psychiatry, vol. 34, no. 5, pp. 443–498, Jul. 2022, doi: 10.1080/09540261.2022.2128725.
[3] PCBS (Palestinian Central Bureau of Statistics), "Energy consumption in the Palestinian Territory, Annual Report," Ramallah, 2016.
[4] F. Mutasim Baba and H. Ge, "Effect of climate change on the energy performance and thermal comfort of high-rise residential buildings in cold climates," MATEC Web of Conferences, vol. 282, p. 02066, 2019, doi: 10.1051/matecconf/201928202066
[5] D. Mitchell, "Climate attribution of heat mortality," Nature Climate Change, vol. 11, no. 6, pp. 467–468, May 2021, doi: 10.1038/s41558-021-01049-y
[6] A. Wadi, M. Alhayek, U. Pont, and A. Mahdavi, "Overheating risk and cooling demand in residential buildings: performance prediction and improvement using a prescriptive approach," MATEC Web of Conferences, vol. 282, p. 02019, 2019, doi: 10.1051/matecconf/201928202019
[7] N. E. KLEPEIS et al., "The National Human Activity Pattern Survey (NHAPS): a resource for assessing exposure to environmental pollutants," Journal of Exposure Science & Environmental Epidemiology, vol. 11, no. 3, pp. 231–252, Jul. 2001, doi: 10.1038/sj.jea.7500165
[8] G. Zittis and J. Lelieveld, "Eastern Mediterranean and Middle East Face Rapid Climate Change," Eos, vol. 103, Aug. 2022, doi: 10.1029/2022eo225026
[9] S. Hajat, Y. Proestos, J.-L. Araya-Lopez, T. Economou, and J. Lelieveld, "Current and future trends in heat-related mortality in the MENA region: a health impact assessment with bias-adjusted statistically downscaled CMIP6 (SSP-based) data and Bayesian inference,"The Lancet Planetary Health, vol. 7, no. 4, pp. e282–e290, Apr. 2023, doi: 10.1016/s2542-5196(23)00045-1
[10] M. Haj Hussein, S. Monna, R. Abdallah, A. Juaidi, and A. Albatayneh, "Improving the Thermal Performance of Building Envelopes: An Approach to Enhancing the Building Energy Efficiency Code," Sustainability, vol. 14, no. 23, p. 16264, Dec. 2022, doi: 10.3390/su142316264
[11] D. Mohaibesh, S. Monna, H. Qadi, and R. Sokkar, "Towards climate resilient residential buildings: learning from traditional typologies," Journal of Physics: Conference Series, vol. 2042, no. 1, p. 012146, Nov. 2021, doi: 10.1088/1742-6596/2042/1/012146.
[12] S. Monna, A. Juaidi, R. Abdallah, A. Albatayneh, P. Dutournie, and M. Jeguirim, "Towards Sustainable Energy Retrofitting, a Simulation for Potential Energy Use Reduction in Residential Buildings in Palestine," Energies, vol. 14, no. 13, p. 3876, Jun. 2021, doi: 10.3390/en14133876
[13] S. Monna, A. Barlet, M. H. Hussein, D. Bruneau, and M. Baba, "Human thermal comfort for residential buildings in hot summer and cold winter region, a user based approach," Journal of Physics: Conference Series, vol. 1343, no. 1, p. 012150, Nov. 2019, doi: 10.1088/1742-6596/1343/1/012150
[14] M. Haj Hussein, S. Monna, A. Juaidi, A. Barlet, M. Baba, and D. Bruneau, "Effect of thermal mass of insulated and non-insulated walls on building thermal performance and potential energy saving," Journal of Physics: Conference Series, vol. 2042, no. 1, p. 012159, Nov. 2021, doi: 10.1088/1742-6596/2042/1/012159
[15] ANSI/ASHRAE Standard-55, "Thermal Environmental Conditions for Human Occupancy," 2017
[16] WeatherShift. (2023). [Online]. Available: www.weathershift.com.
[17] E. Rodrigues, M. S. Fernandes, and D. Carvalho, "Future weather generator for building performance research: An open-source morphing tool and an application," Building and Environment, vol. 233, p. 110104, Apr. 2023, doi: 10.1016/j.buildenv.2023.110104
[18] F. M. Baba, H. Ge, L. (Leon) Wang, and R. Zmeureanu, "Assessing and mitigating overheating risk in existing Canadian school buildings under extreme current and future climates". Energy and Buildings. 2023 Jan 15;279:112710.
[19] B. Bass and J. New, "How will United States commercial building energy use be impacted by IPCC climate scenarios?," Energy, vol. 263, p. 125945, Jan. 2023, doi: 10.1016/j.energy.2022.125945
[20] ANSI/ASHRAE 169-2020, "Climatic data for building design standards," American Society of Heating, Refrigerating and Air-Conditioning Engineers, 2020
[21] Applied Research Institute – Jerusalem (ARIJ), "Climatic Zoning for Energy Efficient Buildings in the Palestinian Territories (the West Bank and Gaza) Technical Report," Jerusalem, Palestine, 2003.
[22] F. M. Baba, H. Ge, L. (Leon) Wang, and R. Zmeureanu, "Do high energy-efficient buildings increase overheating risk in cold climates? Causes and mitigation measures required under recent and future climates," Building and Environment, vol. 219, p. 109230, Jul. 2022, doi: 10.1016/j.buildenv.2022.109230

RISK ANALYSIS AND MANAGEMENT OF UNDERGROUND TUNNELED SMR NPP AGAINST MUNITIONS' HITS

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Abstract

Civil society is increasingly exposed to terror and war threats. The scenario caused by these threats are highly relevant to the continuous performance and safety of Critical Infrastructures (CIs). CIs might be exposed to guided munition hits with high penetration capabilities. Maintaining the continuous performance of CIs is crucial in ordinary times and even more so during emergencies. A passive protective solution is robust and reliable compared to alternative solutions and may be superior over time. Underground structures protect sensitive facilities such as military infrastructures and recently also Nuclear Power Plants (NPPs) from highly explosive charges. The research objective focused on developing a risk-informed optimal decision support methodology for advanced CIs resilience, particularly underground NPPs, exposed to earth-penetrating weapons (EPW) hits. Threat scenario of GBU-28 guided bomb unit (GBU) defined the test case of penetration and detonation above an underground cavern that contains the NuScale Small Modular Reactor (SMR) reactor building. The research methodology was composed of the following phases: literature review; underground critical energy infrastructures vulnerability assessment, focused on SMR; hydro-dynamic numerical simulations of selected threat scenario of underground SMR hit by high explosive warhead, also called munition; analytical-empirical formulation of the in-structure shock; damage assessment of the SMR critical components and its containment structure exposed to munitions' hits; development of fragility curves due to blast waves based on NPP components' tolerance under airplane crash, and seismic fragility curves. The research findings reveal that the severe threat scenario of a GBU-28 hit on the caverned NuScale SMR yield significant Large Radioactive Release (LR) probability of the order of $3 \cdot 10^{-4}$ for peak accelearatipn of 5.2g. This scenario must be further developed for risk mitigation alternatives.

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Keywords: critical infrastructures, NuScale, small modular reactor, munition hit, risk.

1. Introduction

CIs are exposed to gradual increasing scenario of terror and war threats such as high explosive warheads' and missiles hits and ballistic fire. Energy Infrastructures are of particular attention. SMR is considered to be a robust, resilient and safer than the current NPPs and has better resistance to exterior hazards due to its inherent passive safety features. The scenario caused by high explosive warhead threats are highly relevant to the continuous performance, resilience, and safety of (CIs). They are exposed to guided munition hits with high penetration capabilities. Maintaining the continuous performance of critical infrastructures is acute in ordinary times and during emergencies in particular. A passive protective solution is robust and reliable setup comparing to alternative solutions and may be found superior along time. Underground structures are used to protect sensitive facilities such as military infrastructures and recently also NPP's from high explosive charges. The engineering parameters of interest have several degrees of uncertainty and thus are defined as random variables that can be approached with probabilistic, stochastic and computational methods. Common basic engineering concept is that the capacity must be greater than or at least satisfy the demand. While capacity and demand are often conceived as time in-variant parameters, in modern design, which takes structural reliability into consideration, capacity (resistance) is no longer treated as time invariant and thus should be modelled adequately relating to degradation processes e.g. deformations, creep, corrosion & erosion, wear and tear. Tunnels in particular are widely exposed to erosion and water damages. When looking at the demand (applied loads), the randomness and the uncertainty are intuitive, mostly handled by deterministic safety factors. The above leads to the research gap: CIs exposure to munition hit is not sufficiently researched and addressed. Appropriate protection must be designed. Existing risk analysis and risk assessment methodologies for natural and man-made hazards do not cover two intrinsic aspects: 1. Guided bombs threat; and 2. Evaluation of the physical state of the underground protection in the future. Therefore, this research aims to address the research gaps stated above: by taking risk analysis methods to the field of guided bombs threat through an integrated methodology (deterministic & probabilistic/stochastic) and creating blast events fragility curves based on seismic fragility curves and resistance to in structure shock based on airplane hit data A case study of a tunnelled SMR NPP is presented and the results showing the feasibility of the methodology are introduced.

1.1. Research framework

The research objective is focused in the development of a risk informed optimal decision support methodology for advanced CIs resilience, in particular underground NPPs, exposed to EPW hits. The test case was defined by threat scenario of GBU-28 guided bomb unit (GBU) penetration and detonation above an underground cavern that contains the NuScale SMR RXB. The research methodology is composed of the following phases:

- Literature review;
- Underground critical energy infrastructures vulnerability assessment, focused on SMR;
- Hydro-dynamic numerical simulations of selected threat scenario of underground SMR hit by high explosive Warheads;
- Analytical-empirical formulation of the in-structure shock;
- Damage assessment of the SMR critical components to munition hits;
- Development of fragility curves due to blast waves based on NPP components' tolerance under airplane crash, seismic fragility curves, analytical-empirical formulas and numerical simulations;
- Integrated risk analysis of the SMR to the given threat scenario and conclusion.

Evaluation of the risk due to seismic events is carried out using Seismic Margin Analysis (SMA). Its purpose is to provide an understanding of significant seismic vulnerabilities and its scope is the evaluation of seismic fragilities for SSC (Structures, Systems and Components) based on a single module. A ground motion representing High Confidence Low Probability of Failure (HCLPF) is derived for each SSC. Accident sequences from the Probabilistic Risk Assessment (PRA) are solved to produce the combinations of seismic and random failures that could lead to Core Damage (CD) and LR. Cutset level and plant level HCLPFs are then derived using the Min-Max method.

1.2. Importance and innovation of the research

The research lays a base to optimal protection of CIs with a possibility of future upgrade. It should be emphasized that as far as it is known, there is no scientific focus on vulnerability and protection of NPP's to high precision weapons. In addition, underground projects, especially of critical energy infrastructures will become common as urbanization and population density increases. therefore, the test case is also unique.

1.3. Nomenclature

Following are terms of reference in the research topic of risk analysis and protective solutions of NuScale SMR:

Basemat	Raft foundation of the NuScale SMR
BioShield	Removable module placed on top of the SMR Pool for refueling the nuclear module.
CD	Core Damage
CDF	Core damage frequency
CI	Critical Infrastructure
EPW	Earth Penetrating Weapon
EPZ	Emergency planning zone
GBU-28	Guided Bomb Unit
HCLPF	High Confidence Low Probability of Failure
LR	Large Radioactive Release
NPM	Nuclear Power Module
NPP	Nuclear Power Plant
PRA	Probabilistic Risk Assessment
RBC	Reactor Building Crane
RXB	NuScale SMR Reactor Building
SFP	Spent Fuel Pool
SMA	Seismic Margin Analysis
SMR	Small Modular Reactor
SSC	Structures, Systems and Components

2. Literature review

Nuclear Power is an important source of energy, with significant risks to be analyzed and managed. Engineering design is carried out typically as a tradeoff between maximizing safety and minimizing costs. NPPs are relatively safer than ordinary structures, with corresponding high costs, but are not absolutely safe [1]. The design and authorization process defined by the NRC (Nuclear) is well structured and includes a PRA for both internal and external events. SMR in general and NuScale SMR in particular, are designed to withstand external hits using passive safety systems. Winds, aircraft impacts and earthquakes were examined. It was shown that important SSCs are designed to withstand a wind-generated-missile hit and to maintain operational safety. It was also shown that aircraft impact does not significantly affect the risk envelope and was not further examined, while seismic loads at higher than the designed levels may lead to a failure and LR. The fact that the literature review for a munition hit on SMRs yielded only minor findings has two aspects: lack of background and knowledge and the relevance and importance of this issue. Furthermore, the need for further research regarding the resilience of NuScale SMR to blast loads is stressed by the most updated literature found [2]: "Finally, further investigation is deemed necessary in order to study the potential damages of the structure in the case of other hazards such as tsunami events, blast loads, etc."

Although various papers were reviewed for the investigation of the core fragility parameters, suitable fragility parameters were found only for seismic loads. The SMA examined scenarios initiated by seismic events and led to damages of components or to structural events. In contrary to components failure which can be successfully mitigated and thus withstand the hit, the SMA determined that failure of major structural elements directly leads to Core Damage (CD) and to a Large radioactive Release (LR). The SMR analysis shows acceptable design in accordance with the NRC (US Nuclear Regulatory Commission) defined hazards. Beyond design events may endanger the SMR and must be examined carefully to ensure safety goals. Markou & Genco [2] found that the underground rigid structure satisfactorily defends the modules, correlating with the acceleration levels found to be safe in this analysis. Though, James et al. [3] doubted the resilience, claiming that the underground positioning and small size are an advantage in the way that the structure is rigid and can be easily protected, however the disadvantage is that the vulnerability is higher and shock can easily be transferred due to the close positioning of the elements and the CNVs.

In order to examine the vulnerability of a NuScale SMR to a large conventional warhead explosion (GBU-28) a research titled "Vulnerability and protection study of buried SMRs exposed to munitions hit" [4] showed that NuScale SMR cannot withstand a close range internal GBU-28 hit. Thus, building the SMR to withstand this scenario will require appropriate protective solutions such as placing the NPP in an underground tunnel (passive protection). Underground positioning of the NPP has many benefits, such as: protection against external threats, decreasing of pollution materials etc. Placing an NPP in an underground tunnel was examined by Sapir and Rosen [5]. They determined, for a Westinghouse AP1000 exposed to a classified threat scenario, that placing the cavern at a depth of approximately 80 m should protect the NPP adequately. The summary of the data regarding the significant seismic structural failures in NuScale SMR is delineated in Table 1. Parameters include median fragility,

Table 1: Significant seismic structural failures' events and parameters - NuScale SMR

Event	Element	Median (g)	Br	βμ	HCLPF(g)
1	RBC	2.64	0.28	0.39	0.88
2	RXB Ext. Wall	1.92	0.12	0.33	0.92
3	NPM supports	1.98	0.12	0.35	0.92
4	Bioshield	11.62	0.28	0.37	3.99
5	Bioshield (double stacked)	4.05	0.28	0.41	1.30
6	Pool walls	2.31	0.21	0.33	0.95
7	Crane support walls	2.61	0.12	0.34	1.23
8	Bay Wall	2.65	0.12	0.31	1.31
9	Roof	2.22	0.12	0.26	1.2
10	Basemat	3.57	0.27	0.31	1.38

where:

$\boldsymbol{\beta}_r$, Random variable representing the aleatory (inherent uncertainty of the model) variability of the median capacity.
$\boldsymbol{\beta}_\mu$, Random variable representing the epistemic uncertainty (which can be reduced by improvement of data) of the median capacity.
Median - the median capacity in terms PGA (g).
HCLPF - 95% confidence of less than 5% failure probability.

The external manmade events of explosions were compared to those of earthquakes (natural phenomena). Similarities and differences were found and presented. Based on the accelerations received from the simulations and NuScale's seismic fragility analysis, there is a need to create fragility curves for the postulated events, based on the Nuclear Energy Institute publications for dynamic tolerances for an aircraft impact [6]. PPV of 1 m/s was found as a common criterion for cavern exposed to adjacent explosions in order to avoid damages beyond cracking (spalling). Meaning a PPV of 1 m/s can be the threshold value which must be avoided in order to maintain the SMR cavern stability, and will affect directly the depth of burial resulting from the threat.

Common tunneling practices such as shotcrete and rock reinforcement were also reviewed. Tunneling is an important and developing branch of civil engineering which suffer from many forms of deterioration such as water leakage, cracks, deformations and more. Two different studies, one regarding road tunnels in Japan, and the other in China, reported that more than 60% of tunnels in use suffer from different kinds of deficiencies.

2.1. Safety and operational considerations of an underground NuScale SMR

An underground NPP design has many advantages related to security, survivability, and radioactive atmospheric releases in case of hostile activity or severe accidents. However, designing the nuclear island underground imposes additional economical, operational, and safety implications. Several nuclear reactors were built and operated fully or partially underground throughout history [5], [7]. From what is known, some of the underground nuclear reactors experienced severe accidents, including core meltdown and radioactive release (e.g., Lucens experimental nuclear power reactor ([8]; [9], [10]) and Ågesta NPP ([10], [11], [12], [13]). Yet, none of these accidents was attributed to the underground location of the reactor. Moreover, the underground medium proved safer in terms of significant radioactive release.

An underground NuScale design seems feasible in terms of operation and safety. While most safety features are improved, some operational features are worsen. The main implications are summarized in Table 2.

Table 2: The main operational and safety implications of an underground design of the NuScale power plant.

Feature/Issue	Implications on Reactor Operation
Physical separation of the NSSS from the turbine hall	Requires a redesign of the second and third reactor loops, considering the depth of the reactor. Will impact efficiency and profitability of the power station.
Refueling outage	Refueling outage procedures will not be affected; for reducing fuel transport operations, enlarged SF design is recommended.
Control room and I&C systems	Careful design review of the control room and I&C is needed. Safety aspects and emergency plans of the revised control room and I&C location should be examined.
Ventilation	Maintaining proper ventilation is feasible; no significant implications on the safety and operation of the reactor are expected.
Electricity	No significant implications on the reactor operation and safety expected.
Access	Several independent access tunnels, large enough for operational and emergency operations, should be installed.
Routine maintenance	Maintenance operations should be planned taking into account underground conditions. Maintenance operations of the tunnels and underground spaces will have to be carried out.
Feature/issue	**Implications on Reactor Safety**
Geological surveys and seismic activity	Underground facilities are less vulnerable to seismic events.
Passive cooling and shutdown systems	NuScale passive cooling and shutdown systems will not be affected from the underground location.
Emergency Planning Zone	Reduced EPZ is anticipated; enabling sitting in more densely populated areas.
Flooding and fires	Flooding protection means should be introduced for securing facility personnel and safety systems. The limited access to the underground site requires a robust planning of fire fighting solutions.

3. NuScale SMR as an underground facility

A NPP failure would have severe economic, environmental and social consequences. Thus, the need to assure the plant's ability to withstand extreme events is obvious. According to Ornai et al. [14], an extreme event of a direct missile hit could lead to an overall failure of the NPP, which in turn could lead to core meltdown and can be followed by the release of radioactive materials. Smith & Wright [15] determined that underground positioning of the Westinghouse SMR decreases the chance to an event, which will affect the safety of the SMR and, that the passive safety systems can safely stop the nuclear reaction, remove the decay heat and ensure cooling and safe system shutdown in case of an emergency event. The NuScale SMR is a modular PWR (Pressurized Water Reactor) NPP, consists of up to 12 modules (Figures 1÷3). Each module consists of a 45 MWE (Megawatts Electric) reactor and 2 steam generators. The nuclear fuel is UO_2 enriched up to 4.95% and the duration of the fuel life cycle is 24 months. An optional configuration is 540 MWE for 12 modules. Most of the NPP main building is underground, made of high stiffness concrete structure to address earthquakes and aircraft crash impact scenarios. Each power module includes a containment and a reactor vessel, interior helical coil, two steam generators and a pressurizer, all factory manufactured [16]. Each module is installed in its own isolated bay in an underground, stainless steel-lined concrete pool, also referred as Ultimate Heat Sink (UHS).

Due to security-related issues the geometry of NuScale SMR RXB is not available for the open public as detailed in NuScale analysis in Ch. 9 “Withheld Information”. However, NuScale had published in Chapter 3 “Design of Structures, Systems, Components and Equipment”, sufficient data about the finite-element modeling used for estimating the dynamic loadings on the building and for seismic design. The finite-element models provide information such as walls length, walls thickness, building height and more. The most relevant geometrical data is presented in Tables 3 & 4 and in Figures 1÷3.

Table 3: RXB approximated dimensions

Description	Dimension [m]
Total Height	50.9
Total length	106.7
Total width	45.7 m
Ceiling thickness	1.2 m
Floor thickness	3.0 m
Pool height	23 m
Depth below ground	26.2 m

Table 4: NPM dimensions

Description	Dimension
Height	19.8 m
Diameter	4.4 m
Thickness	7.6 cm

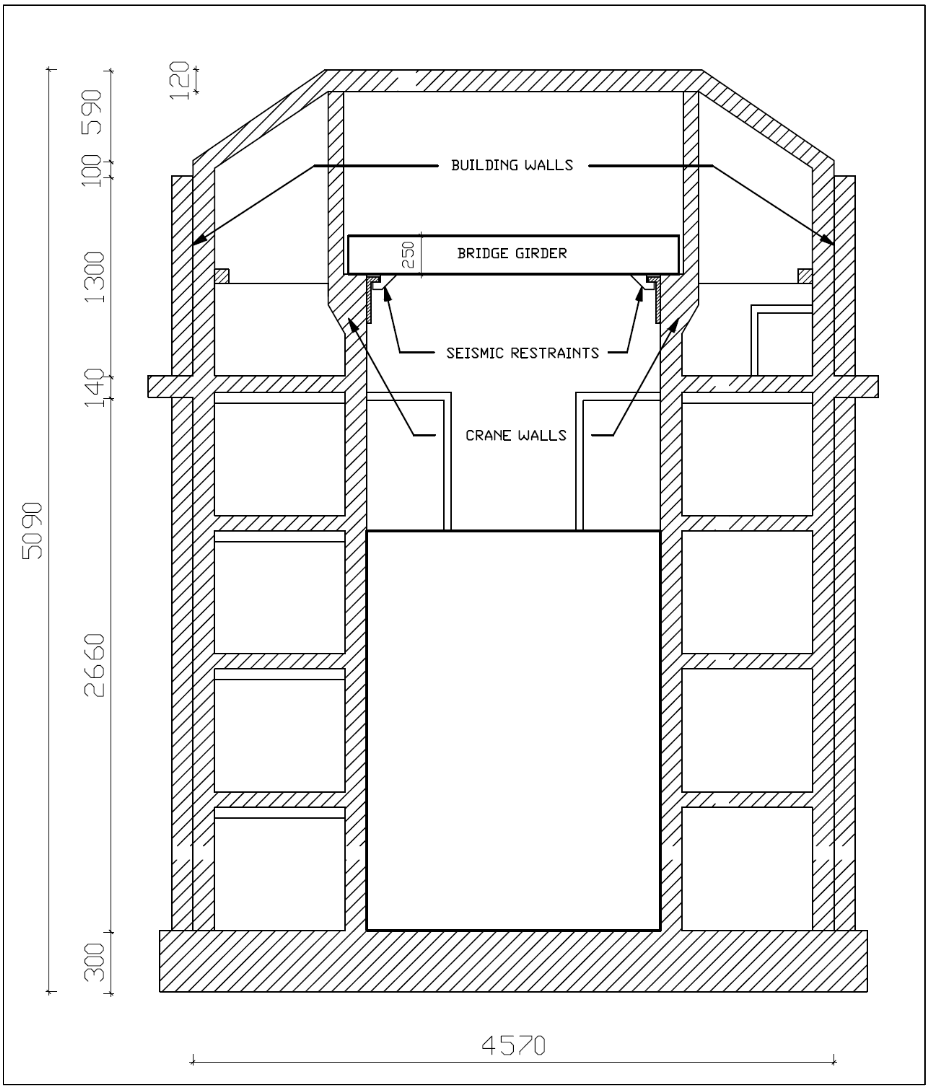


Fig. 1: RXB vertical cross-section, not to scale (dimensions are in cm)

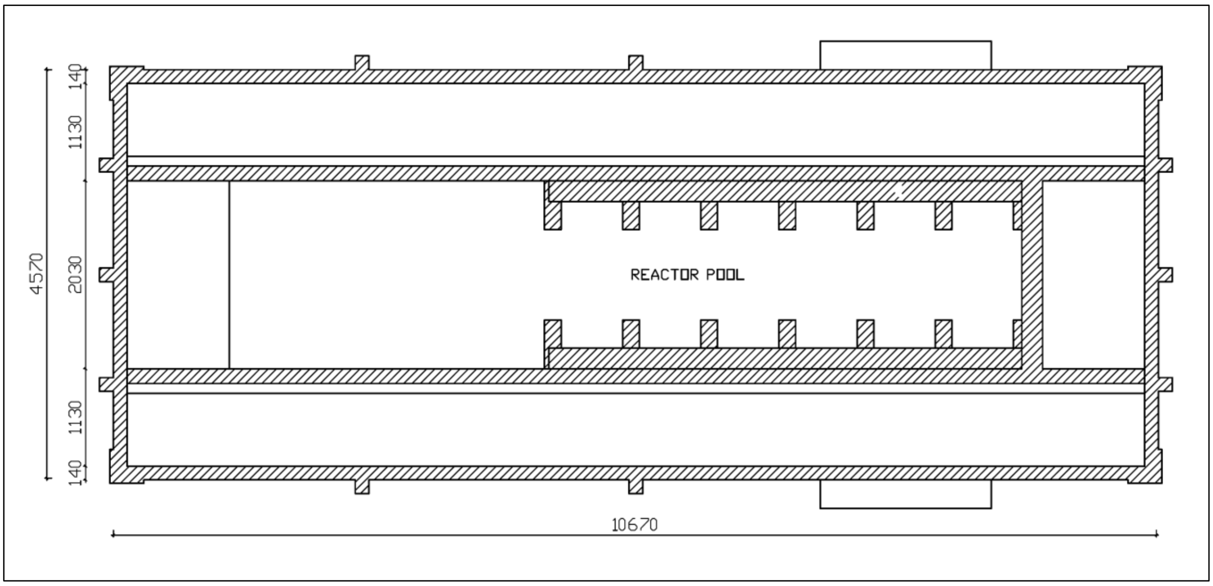
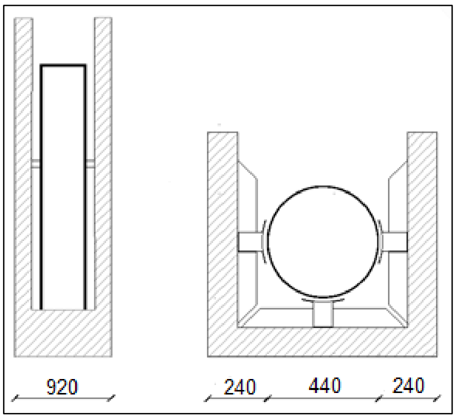


Fig. 2: RXB Horizontal cross-section, not to scale, dimensions are in cm



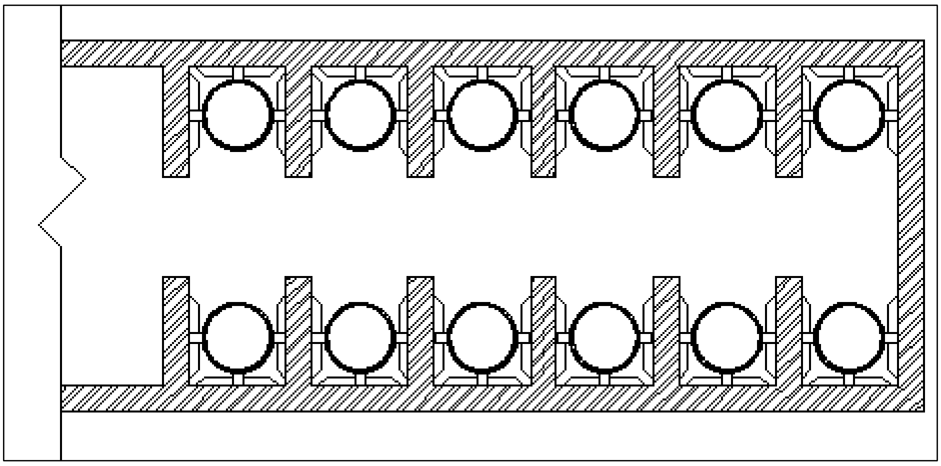


Fig. 3: Horizontal cross section of the bay walls and the NPMs, not to scale. Enlarged vertical and horizontal section of single bay wall and the NPM is shown above, all dimensions are in cm.

4. Threat scenario

This research referred to a threat scenario of GBU-28 as follows: the Guided Bomb Unit 28 (GBU-28) was developed in the USA and has been in use since the first Gulf War (1990-1991). It was designated to hit underground shelters. The bomb can penetrate more than 30 m of soil and 6 m of concrete (Ornai et al., 2014). According to Global Security Website [17], the weight is 647 lb Tritonal, which is equivalent to 299 kg TNT (Table 5). The bomb penetrates to the rock, and thus creates full contact, transferring the energy to the adjacent rock - fully coupled charge. The main input parameters for our analysis are the high explosive content and the penetration depth. We assume a TNT explosive mass of 299kg, in the shape of a two-meter-long cylinder. The energy content of the TNT explosive is taken as 4.3MJ/kg. The depth of penetration was taken as 11m. Fig. 4 depicts the vertical layout of the GBU-28 threat scenario for a tunnelled configuration of NuScale SMR. The NPP is assumed to be buried in a depth that would reduce the effect of the underground shock created by the bomb to an acceptable level for the NPP. Fig. 5 depicts velocity field at time of 80 ms, the blast front has reached a depth of 175m, and the front peak is 0.3m/s. As the blast wave progresses with time, all parts of the building are set into motion, in this set also the air into motion, as can be seen by colored spaces. To assess the risk to the NPP, a set of interest points is defined, where time history data is gathered for the velocity components. The set of interest points are shown in Table 6 and Fig. 6 (for the NPM support-pool wall): The time history of all points exhibit a typical pattern. They vertical velocity oscillates at high frequency, which may be attributed to the structure natural frequencies. Most of the velocity time histories are between (-0.1m/s) to (+0.1)m/s. In the displacement time-history these high frequencies are smoothed. The displacements are between (-0.10mm) to (+0.15)mm. Derivation of the acceleration levels related to these time-histories is obtained by differentiating the displacement curve twice with respect to time.

Table 5: Parameters of GBU-28

Total Weight	2,132 kg
Explosive's Weight	299 kg
Length	7.6 m
Diameter	35.6 cm

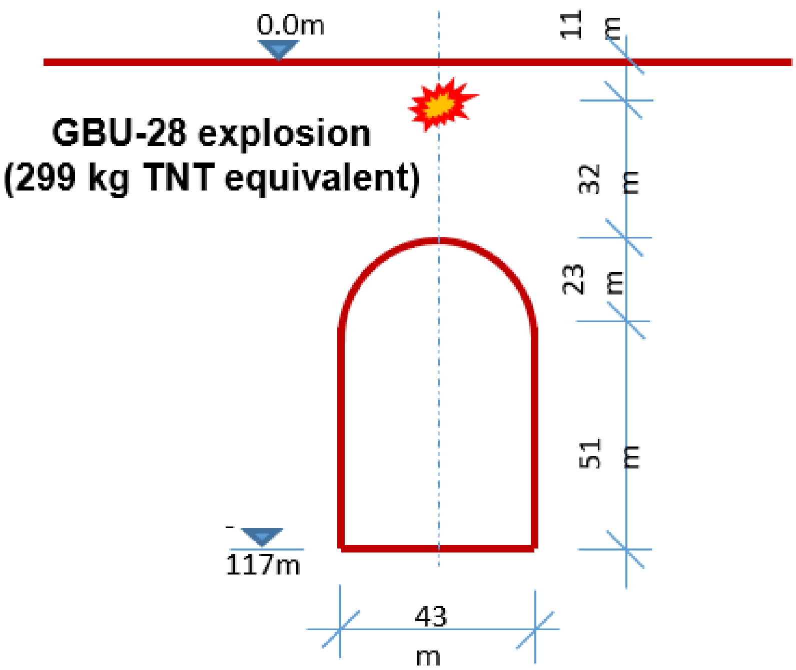


Fig. 4: Vertical section that presents the underground cavern, with its typical distances from the explosion location of a GBU-28.

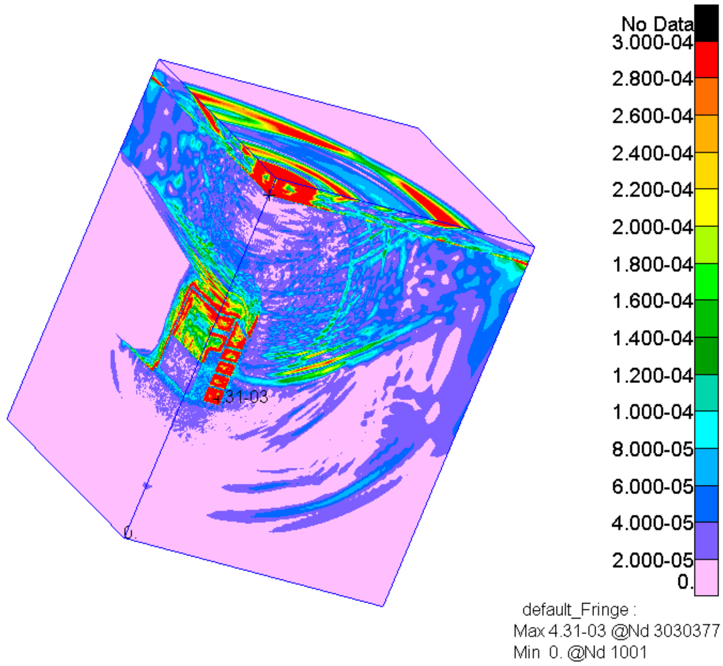


Fig. 5: Particle velocity field at 80ms. Scale in m/ms

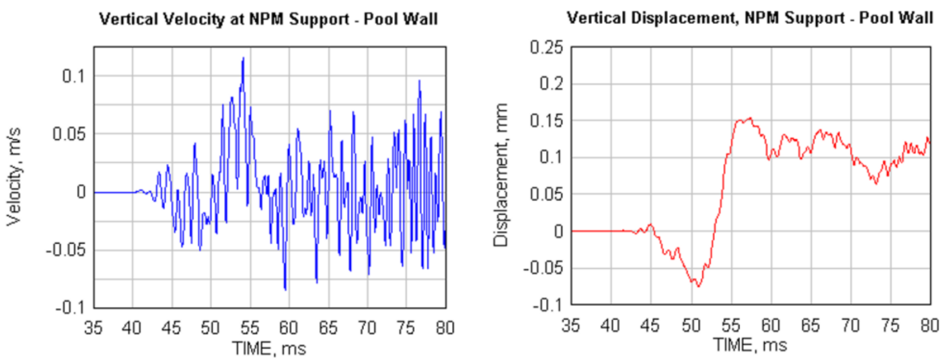


Fig. 6: Vertical velocity and displacement time histories at the NPM support, pool wall side

Table 6: Summary of acceleration parameters and maximal values for the threat scenario

POINT	ω_1, s^{-1}	d_1, m	ω_2, s^{-1}	d_2, m	acc_1, g	acc_2, g
1 Vertical	607.4	$4.23 \cdot 10^{-5}$	485.0	$9.34 \cdot 10^{-5}$	1.6	2.2
2 Vertical	794.3	$4.18 \cdot 10^{-5}$	419.1	$4.12 \cdot 10^{-5}$	2.6	0.72
3 Vertical	1017.	$2.61 \cdot 10^{-5}$	1620	$1.14 \cdot 10^{-5}$	2.7	3.0
4Vertical	922.6	$3.47 \cdot 10^{-5}$	458.2	$4.91 \cdot 10^{-5}$	3.0	1.0
5 Vertical	300.9	$2.51 \cdot 10^{-4}$	607.2	$3{,}93 \cdot 10^{-5}$	2.3	1.5
6 Vertical	535.1	$3.69 \cdot 10^{-5}$	129.8	$3.74 \cdot 10^{-4}$	1.1	0.63
7 Vertical	1184	$2.12 \cdot 10^{-5}$	872.2	$2.39 \cdot 10^{-5}$	3.0	1.8
7 Lateral	534.9	$2.47 \cdot 10^{-5}$	426.0	$2.50 \cdot 10^{-5}$	0.70	0.45

The summary of all the data regarding the significant structural failures is shown in Table 7, based on NuScale Power LLC (2020), Standard Plant Design Certification Applications, Ch. 19 rev. 5 [18].

Table 7 summarizes the 8 points of interest with dynamic parameters of assessment.

Table 7: Final list of the points of interest

Chosen Points	Description	Time History of ground shock and motion parameters
#1	RXB Crane Support	Velocity, Acceleration
#2	NPM supports – Bay Wall	Velocity, Acceleration
#3	NPM supports – Pool Wall	Velocity, Acceleration
#4	Bioshield	Velocity, Acceleration
#5	Basement	Velocity, Acceleration
#6	RXB Ext Wall	Velocity, Acceleration
#7	SFP floor	Velocity, Acceleration
#8	Cavern top	Velocity, Acceleration, Pressure

4.1 Preliminary results demonstarting the methodology feasibilty

The SMA defines criteria for different structural events which can lead directly to overall failure. The SMR components' capacity parameters (HCLPF, βμ, βr) and their resilience and controlling failure modes under seismic events are shown in Table 1. The published data regarding the seismic capacities reveals that core damage (CD) and a Large Release (LR) of radioactive materials to the atmosphere would occur at a certain Peak Ground Acceleration (PGA) greater than the dynamic capacity of the critical components and structural elements. Eight different points of interest were finally selected for the analyses (Table 7 and Fig.s 7-8).

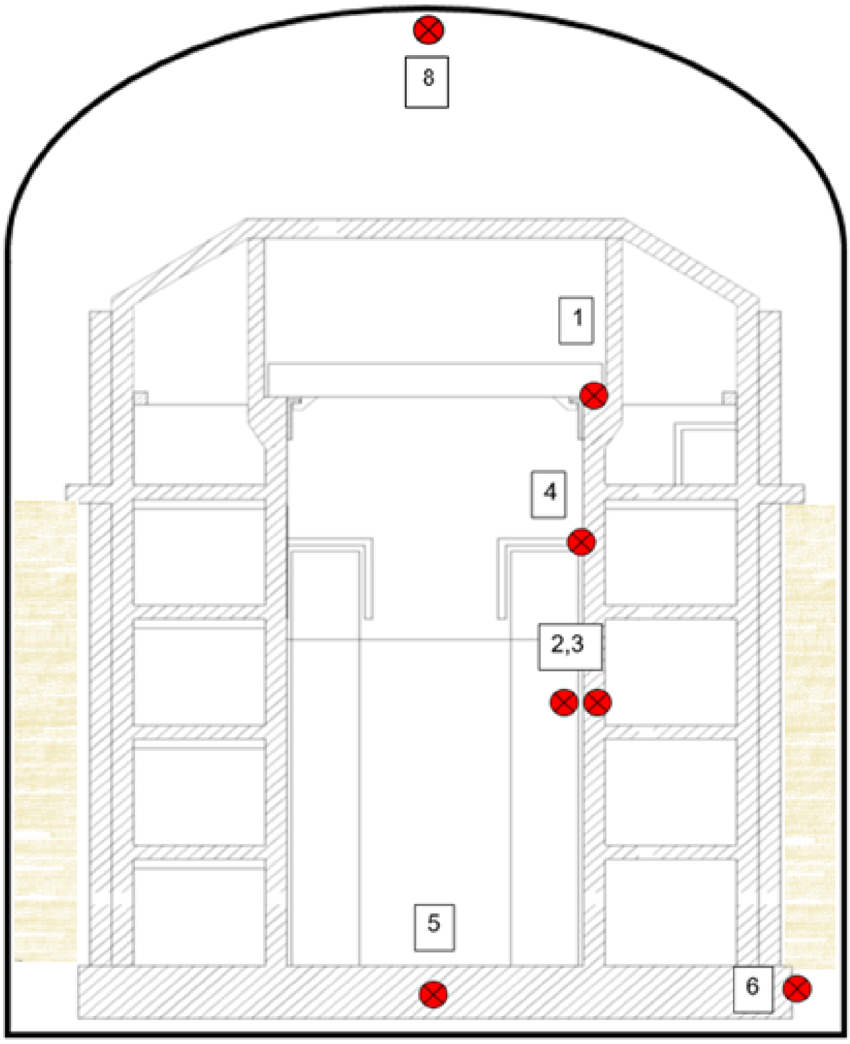


Fig. 7: RXB vertical cross section with the selected points of interest. Not to Scale. Detailed dimensions are shown in Fig.s 1-3.

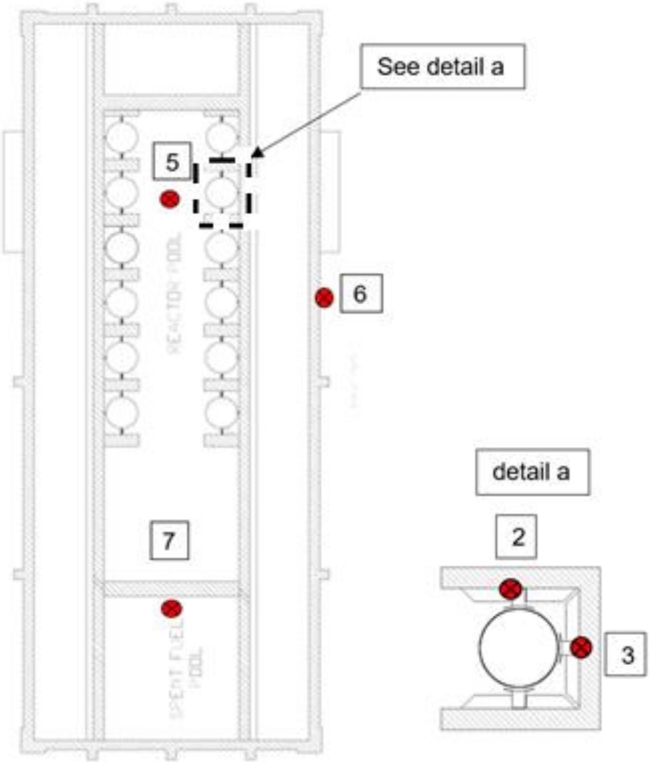


Fig. 8: RXB and NPM horizontal section with the selected points of interest. Not to Scale. Detailed dimensions are shown in Fig.s 1-3.

4.1.1 Preconditions and assumptions for the reconstruction of NuScale seismic fragility curves

- All median capacities are lognormally distributed;
- The median [θ = exp(μ)] is taken from the SMA data and thus the mean of the underlying function (with normal distribution) is ln(θ) that is equal to μ;
- The uncertainty parameters are defined by $\beta = \sqrt{\beta_r^2 + \beta_\mu^2}$;
- There is a similarity between the uncertainty parameter β of the lognormal distribution and the coefficient of variance for the normal distribution;
- In this work σ is assumed as β explained herein:
  The coefficient of variance is $\frac{\sigma}{\mu}$ assumed as equal to β, means that $\sigma = \beta\mu$;
  The median capacity θ values are assumed as equal to base e, means that their natural logarithms are close to ln(e) which equals to 1. Thus $\mu \cong 1$ and $\sigma \cong \beta$;
- Note that σ has the same units of μ since β is a dimensionless parameter and it is multiplied by μ units.

4.2 Reconstruction of Nuscale SMR seismic fragilty curve HCLPF at 0.95 confidence margin

Further on the demonstration for the 1st point (RXB Crane Support) is shown. Fig. 9 presents the reconstructed fragility curve based on NuScale's data for a seismic event (See point #1 in Tables 1, 6 & 7). The extracted HCLPF of 0.88g is in line with the HCLPF of the NuScale SMA.

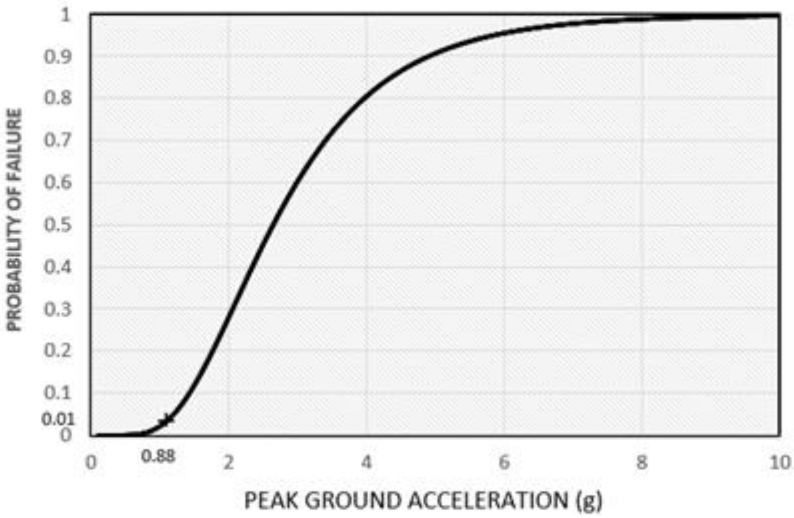


Figure 9: Reconstruction of the RXB Crane Support (point #1) seismic fragility curve

According to The NEI shock damage categories supply median fragility limits (accelerations) which vary in the range of 27g-200g. The most sensitive category of NPP equipment such as generators has a median acceleration of 27g. This value is validated by another source [19], which determines that the shock tolerances for heavy machinery is in the range of 10-30g. The median value is than combined with uncertainty parameters from the seismic fragility curves, assuming similar dynamic response of the structure to both phenomena. Figure 10 demonstrates the adapted fragility curve, with a median acceleration of 27g and uncertainty parameters of (βr= 0.28 $\beta\mu$ =0.39).

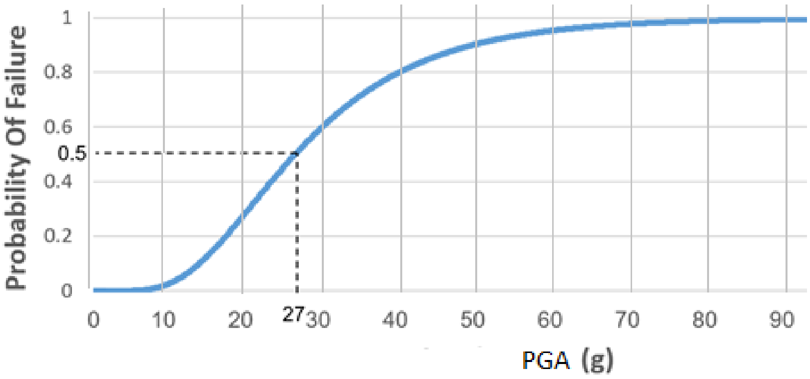


Fig. 10: RXB Crane Support modified fragility curve (assuming median equals 27g)

4.3 Posting the modified fragilities into the shock spectrum

Fragility results are posted on a shock spectrum in order to assess the probability of failure. The main concern in the design of SMR RXB protective structure is to prevent a structural failure. Regarding blast events: when a structure is exposed to blast impact, a shockwave is transmitted through the rock media and then passes to the RXB and causes in-structure motions (displacements, velocities and accelerations). It may be harmful to many kinds of the SMR components and structural elements. The results received from the fragility curves (various accelerations with probabilities of failure) were posted in Fig. 11 and 12 demonstrating various accelerations with probabilities of failure.

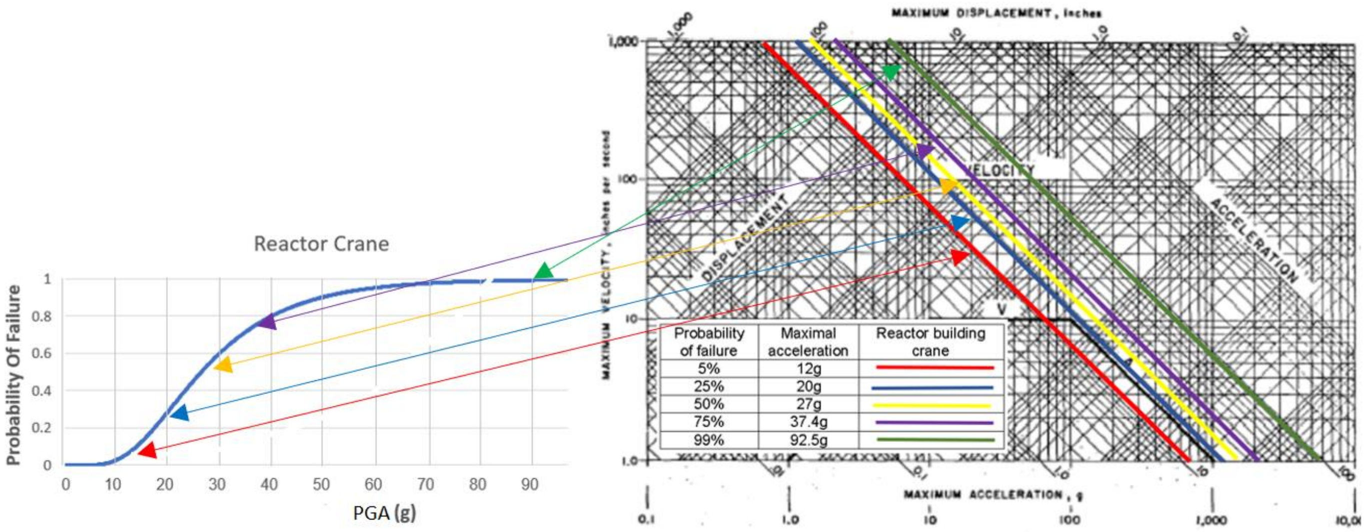


Fig. 11: Fragility curve for the RBC supports (median equals 27g)

Fig. 12: Shock spectrum for the RBC supports (median equals 27g)

5. Results and conclusions

Posting the spectral accelerations in the fragility function yielded the probability of failure of $3{\cdot}10^{-4}$ for 5.2g. In addition, one can see in Figures 10 and 11 a range of in-structure motions which act on the systems and the components of the NPP SMR. The results reveal that given the assumed uncertainty parameters and the 27g RBC median fragility, there are probabilities of less than 1% of failure. If we were dealing with seismic accelerations, these results were lower than the HCLPF (PGA at which there is 95% confidence that the conditional failure probability is less than 5%) and do not fulfill the NRC performance design citeria of CDF (Core Damage Frequency) less than $1{\cdot}10^{-4}$/year. Fuerthermore, the SMR RXB underground tunneled configuration and depth of burial were determined in this research to maintain a PPV of less than 1 m/sec in order to prevent spalling.

Despite the suggested underground configuration and the above results, there is vulnerability of the SMR to the scenario due to two reasons:

1. PGA's are horizontal, while in the postulated scenario, the accelerations and displacements are vertical and may harm the RBC supports or remove the RBC from its supports.
2. Hydro Dynamic simulation results show uunfiltered results of 10-50 (g) which are much higher than the empirical results. The probability of failure in the SMR components is 0.85. It should be pointed out that these are very low duration peak results that may or may not affect the structure, a topic that needs further investigation as an independent and important research topic.

The research finidings follows former studies on the topic that emphasize the need for tools and strategies to validate the redistance of energy CI to munitions' hits [20[, [21], [22].

6. Acknowledgements

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7. References

[1] H. Haldar & S.Mahadevan. "Probability, Reliability and Statistical Methods in Engineering Design". John Wiley & Sons, Inc. 2000.

[2] G. Markou and F. Genco. "Seismic Assessment of Small Modular Reactors: NuScale Case Study for the 8.8Mw Earthquake in Chile". Nuclear Engineering and Design, Vol: 342, 2019. Pages: 176-204.

[3] R.J.James, J.Parker, R.Hill, J.Wiesner and J. Groome. "Aircraft Impact Considerations for NuScale SMR Plant Design". Small Modular Reactors Symposium Washington, DC, USA. 395-404. 2011. DOI:<10.1115/SMR2011-6635>.

[4] D. Ornai, Y. Kivity, E. Gilad, S. M. Elkabets, G. Shany, B. Tavron, I. M. Shohet, and R. Levy. "Vulnerability of Partially Buried NuScale Small Modular Reactor to Internal Munition Hits". the 30th conference of the Nuclear Societies in Israel, June 7-9, 2022, Herzliya, Israel. https://events.eventact.com/dan/34300/uploads/INS_Abstract_Book_31.8.pdf.

[5] D. Sapir, and A. Rozen, A preliminary feasibility study of the possibility to burry underground AP1000 NPP in Shivta-Rogem site. A research report for the Ministry of National Infrastructures, Energy and Water, 2015 RD-29-15.

[6] NEI. "Methodology for Performing Aircraft Impact Assessments for New Plants Designs". NEI 07-13, Revision 8P. 2011, ERIN (Engineering & Research Inc.).

[7] G. Petrangeli, Nuclear Safety, 2nd Ed., 2019. Butterworth-Heinemann, chap. 21, Underground Location Of Nuclear Power Plants.

[8[E. N. Shaw. Europe's Nuclear Power Experiment, History of The OECD Dragon Project, 1983. Pergamon Press.

[9[International Atomic Energy Agency (2006). Decommissioning of underground structures, systems and components, Technical Reports Series No. 439, pp. 76, 123-136.

[10] International Atomic Energy Agency. On-site disposal as a decommissioning strategy, 1999. IAEA-TECDOC-1124.

[11] B. Grönwall, L. Ljungberg, W. Hübner, and W. Stuart, (1967). Intercrystalline stress corrosion cracking of inconel 600 inspection tubes in the Ågesta reactor, Nuclear Engineering and Design 6(4), 383-390.

[12] E. Aalto, R. Sandlin, Å. Krell, Some comparisons of measured and predicted primary radiation levels in the Ågesta power plant, Nuclear Engineering and Design 8(3), 1968.391-401.

[13] C. Dahlgren, The Flooding Incident at the Ågesta Pressurized Heavy Water Nuclear Power Plant, SKI Report 96:51. (1996).

[14] D.Ornai, E.Gal, Y.Ronen, and I.M. Shohet, "Nuclear power Plant (NPP) Protection alternatives against hostile events and their safety & operational implications", Ministry of Energy and Water (National Infrastructures), 2014. Contract No. 879/8196/99 (104 pages).

[15] M. C.Smith, R. F.Wright "Westinghouse Small Modular Reactor passive safety system response to postulated events," In: Proceedings of the 2012 International Congress on Advances in Nuclear Power Plants - ICAPP '12| 2799 p.

[16] J. N. Reyes and E. Young 2012 "The NuScale Advanced Passive Safety Design," ASME 2011 Small Modular Reactors Symposium, September 28–30, 2011, Washington, DC, USA https://doi.org/10.1115/SMR2011-6658.

[17[Global Security Website (2020), <Guided Bomb Unit-28 (GBU-28) Bunker Buster - Smart Weapons (globalsecurity.org)< July 20th 2022.

[18["Chapter Nineteen: Probabilistic Risk Assessment and Severe Accident Evaluation," Nuscale DCA, Docket #52-048), Rev. 5, Agency-Wide Document Access and Management System Accession Number ML20224A508 (July 2020); https://www.nrc.gov/reactors/new-reactors /smr/nuscale/documents.html (June 21, 2021).

[19] U.S. DoD 2008, "Structures to Resist the Effects of Accidental Explosions," Unified Facilities Criteria, United States of America, Department of Defense, Washington, DC, UFC 3-340-02.

[20] D. Ornai, S. M. Elkabets, Y, KivityI, G. Ben-Dor, L. Chadad, E. Gal, B. Tavron, E. Gilad, R. Levy, and I. M. Shohet. "A methodology of risk assessment, management and coping actions for Nuclear Power Plant (NPP) hit by high-explosive warheads", Advanced Engineering Informatics (Special issue on Constructing Smart Cities) Volume 46, October 2020, 101192. https://doi.org/10.1016/j.aei.2020.101192.

[21] X. Yao, H-H Wei, I. M. Shohet, and M. Skibniewski. "Assessment of Terrorism Risk to Critical Infrastructures: the Case of a Power-Supply Substation". Appl. Sci. 2020, 10, 7162; doi:10.3390/app10207162.

[22] A. Urlainis, D. Ornai, R. Levy, O. Vilnay, and I. M. Shohet. "Loss and damage assessment in critical infrastructures due to extreme events", Safety Science 142, 2022, 105587. https://doi.org/10.1016/j.ssci.2021.105587.

NEGATIVE CARBON CONCRETE FOR ACHIEVING NEXT GENERATION OF SUSTAINABLE AND DURABLE MODULAR INTEGRATED CONSTRUCTION (MIC): A REVIEW

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Abstract

Sustainable construction is currently in much demand as construction industry produces a huge amount of carbon dioxide (CO_2), exacerbating global warming. Modular integrated construction (MiC) is set to become a prominent solution to achieving the "carbon neutrality" initiative in Hong Kong, offering high productive efficiency. The concept of "low carbon construction" is proposed by the use of low carbon construction materials and the optimization of project management. However, there remains great potential in the use of these methods in reducing carbon footprint during the design and construction process. This paper firstly reviews possible pathways to reducing the embodied carbon of reinforced concrete. A novel concept known as "negative carbon concrete", which is potentially achieved by combining CO_2 mineralization – the natural carbonation of concrete with other low-carbon construction materials – is proposed. The durability performance of fiber reinforced polymer (FRP) bar-reinforced concrete can be improved by concrete carbonation. The application of negative carbon concrete in MiC is discussed from material-level to urban-level. Analysis indicates that negative carbon concrete may be used to achieve next-generation sustainable and durable MiC.

Keywords: negative carbon construction; modular integrated construction (MiC); carbon dioxide mineralization; basalt fiber reinforced polymer (BFRP); supplementary cementitious material (SCM).

1. Introduction

The climate change problem has aroused extensive attention in recent decades. Currently, excessive carbon emission is regarded as the primary contributor to global warming [1]. The Chinese government presented the "dual carbon" objective in 2020, aiming to achieve carbon peak and carbon neutrality in 2030 and 2060, respectively [2]. Carbon emissions from construction materials account for over 10% of global carbon emissions, rising to approximately 40% when the whole life cycle of building is considered [3]. Therefore, reducing carbon footprint of construction projects is urgent. Environmentally-friendly construction materials and low-carbon-oriented engineering management towards the reduction of carbon emissions in civil engineering have been proposed. Industrial by-products, including mine tailing (MT), fly ash (FA), granulated grounded blast furnace slag (GGBS) and silica fume (SF) are added to concrete to reduce cement dosage. Results show that these materials can effectively reduce the carbon emission of concrete [4-6]. From the aspect of project management, building information modelling (BIM) provides a reliable way to collect project information. By combining BIM with embodied carbon datasets [6], the carbon footprint of a project can be well monitored and controlled.

Current studies can reduce the construction industry's carbon footprint but are inadequate when considering the goal of the "low carbon" concept of "dual carbon". When construction consumes rather than releases CO_2, the carbon footprint is negative. At this point, negative carbon construction is much closer to the "carbon neutrality" goal than low carbon building.

Modular integrated construction (MiC) – a game-changing construction approach popular in Hong Kong – has the advantages of high quality, productivity and safety [7]. This paper coins the novel concept of "negative carbon concrete" and is aimed at the pioneering development of sustainable MiC construction projects. Where "negative carbon concrete" is advocated in MiC projects, the entire design theory should be adjusted [8]. Detailed upgrades in design and construction are divided into four categories, focused on materials, MiC components, single projects and large-scale implementation. Related research papers are reviewed in each section and technical details are discussed.

2. Negative carbon-oriented design of concrete

2.1. Admixture design

Concrete admixtures are used to improve the performance of concrete [9]. From the perspective of embodied carbon, chemical admixtures, including superplasticizers, contribute significantly to the carbon emission of concrete [10]. Conversely, mineral admixtures are generally natural minerals or industrial by-products, which reduce costs and potential carbon footprint [4].

Recently, carbon mineralization has been found to be the most effective and natural way to capture carbon dioxide [11]. Reactions between CO_2 and minerals produce solid carbonates, by which CO_2 is captured and fixed permanently. The carbonation reaction can be completed directly or carried out in two steps. The former can take place during either a liquid or solid phase, but the latter only occurs in a "pH-swing" solution [12]: an initially acidic solution which "swings" to alkaline with the addition of a base. The two-step method is described by Eqs. (1) and (2):

$$\text{Acid} + \text{CaO}\cdot\text{MgO}\cdot\text{SiO}_2 \rightarrow \text{Ca}^{2+} + \text{Mg}^{2+} + \text{SiO}_2\downarrow + \text{H}_2\text{O} \tag{1}$$

$$\text{Base} + \text{Ca}^{2+} + \text{Mg}^{2+} + \text{CO}_2 \rightarrow \text{CaCO}_3\downarrow + \text{MgCO}_3\downarrow \tag{2}$$

During the mineralization process, minerals and industrial CO_2 are consumed. The generated amorphous SiO_2 is of a nano dimension and possesses pozzolanic reactivity, which can be added to concrete as a supplementary cementitious material (SCM) to improve concrete quality [13]. The nano $CaCO_3$ generated in step (2) can be used to modify durability and workability of concrete while $MgCO_3$ can improve its fire-resistance [14,15]. Limestone calcined clay cement (LC^3) is another type of SCM, made from the same raw materials as ordinary Portland cement (OPC), but its calcination temperature is half that required by OPC [16]. Thus, LC^3 can significantly reduce carbon emissions by replacing OPC.

2.2. Aggregate design

Recycled aggregate (originally construction and demolition waste) represents a low-carbon alternative to traditional aggregate [17], contributing less to carbon emission as its embodied carbon belongs mainly to the demolished construction. Moreover, the carbonation of aggregate can further reduce carbon footprint. By injecting CO_2 into recycled aggregate and curing concrete containing recycled aggregate in a CO_2 environment, carbon can be fixed within aggregate [18].

According to recent studies, the mechanical properties and durability of recycled aggregate cannot compete with those of natural aggregate, mainly because old, hydrated cement attached to aggregates substantially weakens bonding strength at transition zones. Carbonation may provide a perfect holistic alternative to recycled aggregate. Apart from CO_2 absorption, the mechanical properties and durability of aggregate are observed to be improved following carbonation [18,19].

2.3. CO_2-embedded concrete design

Foam concrete is a special type of concrete filled with densely distributed air voids. Foam concrete performs well in heat insulation and fire proofing and is durable against freeze-thaw cycles [20]. By replacing air with CO_2, foam concrete can consume embodied carbon while maintaining good durability.

In addition to the absorption of CO_2, CO_2-embedded foam concrete offers other advantages. Firstly, concrete carbonates during contact with CO_2 voids and alkalinity decreases consequently. Lowering the pH value can protect FRP bar from alkaline corrosion. Then, with the blended CO_2, functionalities of concrete generally increase. Workability is improved when cement mortar is fresh, and concrete durability is further improved as carbonation densifies the microstructure of the concrete surface [21].

2.4. Utilization of BFRP bar in negative carbon concrete

Following CO_2 absorption, concrete carbonation occurs and results in higher probability of steel corrosion. To mitigate the corrosion of reinforcement, it is suggested that steel rebar is replaced with FRP bar, which is more robust in neutral environments. CFRP bar is a common type of FRP bar, whose mechanical properties and durability are robust compared to those of steel and other types of FRP. GFRP is also a commonly used construction material. The global warming potentials (GPW) of these materials are concluded in Fig. 1. On a volumetric point, CFRP has a high carbon emission factor of 25 ~ 55 ton CO_2 eq/m^3. The factor of steel is only 8 ~ 20 ton CO_2 eq/m^3 [22].

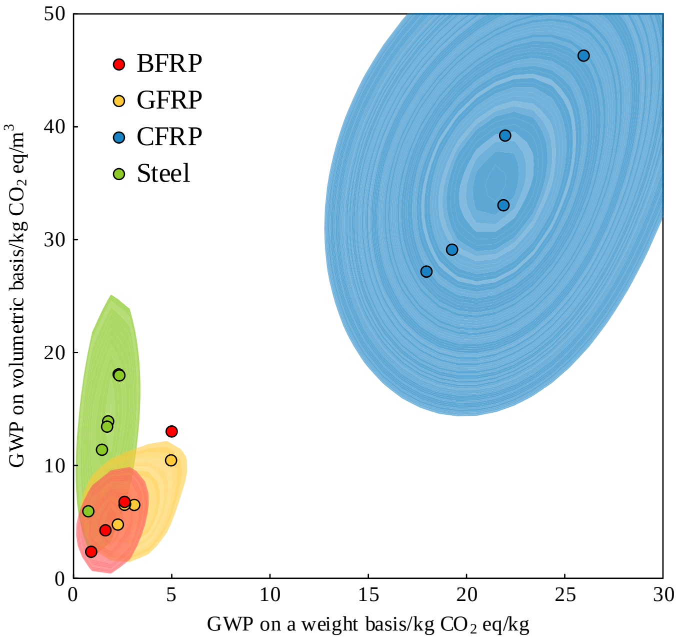

Fig. 1. Comparison of carbon emission factors of FRPs and steel on weight and volume bases.

Although BFRP is less competent than CFRP in terms of mechanical performance, its carbon footprint accords with the “negative carbon” idea. Carbon emission factor of BFRP falls between 2 and 10 ton CO_2 eq/m^3, which is only half that of steel. Studies have revealed that the mechanical properties and durability of BFRP remain reliable in their application to civil structures [23] but it is noteworthy that creep rupture is a prominent problem in the application of BFRP bar. Current studies have revealed that this problem can be addressed by concrete carbonation, whereupon the alkaline corrosion problem of BFRP is alleviated as the pH value of pore solution decreases [24].

2.5. Key criteria for design of negative carbon concrete

2.5.1. Bond behaviors between BFRP bar and concrete

Bond strength is a key parameter for consideration in the design of BFRP bar-reinforced concrete. Bond strength does not depend on fiber type or bar diameter [25]. The principal influencing factors of bond behavior are axial stiffness and the surface treatment of BFRP bar. When considering axial stiffness, BFRP bar has the highest bond strength, compared with GFRP and CFRP. Proper surface treatments, such as coating and deformation, are beneficial to bond behaviors. In addition, environmental factors also influence bond behaviors [26]. Bond length between BFRP bar and concrete can be shortened under harsh environments. Shorter bond length results in higher traction force, and a greater probability of combined failure. Thus, these factors should be considered in design for reliable bonding.

2.5.2. Crack Control Design

The main causes of concrete cracks are shrinkage, sharp temperature gradient and excessive loading. The first two factors relate to raw materials and curing conditions, and the final reason concerns the difference between external loading and the tensile strength of concrete [27]. Since nano SiO_2 and certain other SCMs are added to concrete, the cement dosage is lower. Early shrinkage and temperature gradient conditions will cause partial weakening as less cement is used. For negative carbon concrete to be less susceptible to excessive external loading, some regular approaches work well, including increasing reinforcement, prestressing tendons and using crushed aggregate [28]. However, due to differences in its properties from those of steel, the short- and long-term performance of prestressed BFRP tendons should be carefully studied.

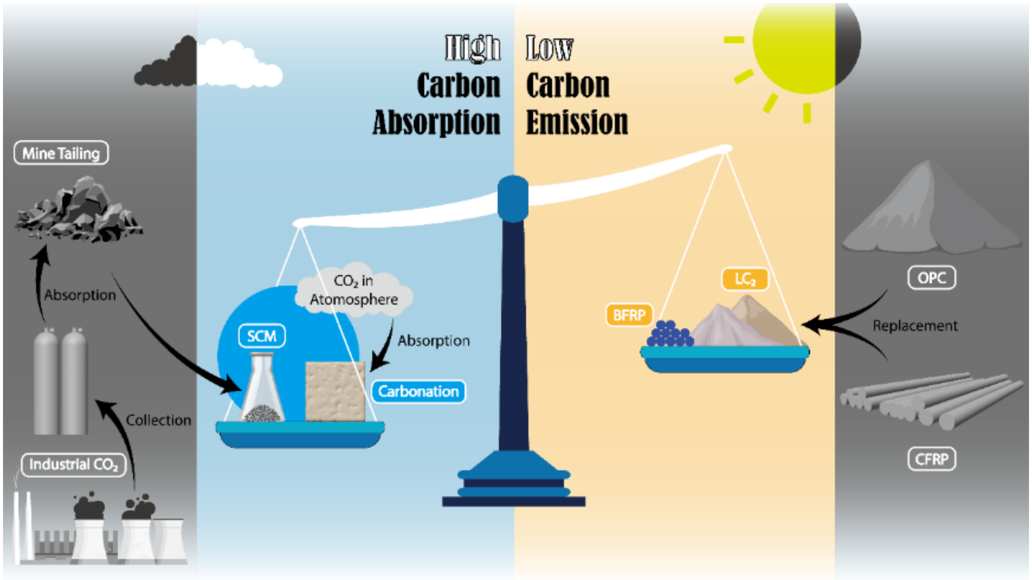

Fig. 2. Design scheme of negative carbon concrete.

2.5.3. Creep rupture behaviors of BFRP bar

An important factor controlling the design of BFRP-reinforced components is creep rupture, a failure mode in which bar rupture occurs abruptly after long-term loading [29]. Factors influencing creep behavior mainly concern the magnitude and duration of loading [30], whereby it is more likely to occur when the magnitude is higher or the duration is longer. Other factors affecting creep rupture failure modes include certain environmental variables [23]. When environmental conditions are detrimental to fiber or resin, the creep behaviors of BFRP are negatively affected. Hence, not only should the creep behaviors of BFRP bar be thoroughly researched, but environmental factors and load parameters should also be considered at design stage.

A novel proposal of achieving negative carbon concrete is illustrated in Fig. 2. CO_2 is absorbed through CO_2 mineralization, CO_2-embedded foam and natural carbonation. Carbon emission is also reduced by replacing CFRP or steel bars with BFRP bars, and by replacing Portland cement with LC^3. When CO_2 absorption is higher than CO_2 emission, a negative carbon footprint can be achieved at reinforced concrete level.

3. Pivotal design strengthening performance of negative carbon components of MiC

3.1. Mechanical properties

Mechanical properties are the priority when negative carbon components are designed. Typical mechanical properties requiring consideration are axial mechanical properties, bending performance and resistance to dynamic loads. Since the compressive strength and elastic modulus of BFRP are lower than those of steel, axial compressive performance and flexural stiffness are inferior to those of steel-reinforced concrete (RC) components [31]. Special consideration is required to offset these degraded properties. In contrast, due to higher flexibility, BFRP-embedded components perform better under dynamic loads [32].

3.2. Demountable and reusable MiC

From the perspective of life cycle, the carbon footprint of a MiC project can be further reduced by reutilizing components from previously demolished projects. The key to reusable MiC components is a demountable connection. Similar to traditional modular construction, critical designs for reusable MiC should focus on connections between beams and walls, and between walls and foundations, as well as between different walls [33]. Fewer studies have investigated connections between beams and slabs. For future research, different types of joint for MiC components should be thoroughly investigated.

3.3. Performance under harsh environments

Performance degradation under harsh environments is a crucial area in the application of BFRP-reinforced carbonated SCM concrete (BCS). Since SCM is added to cement paste, and carbonation forms a thin layer of densified $CaCO_3$, the durability of BCS is theoretically superior to that of OPC [21]. However, the long-term performance of BCS under severe environmental conditions has yet to be systematically studied. Thus, the durability of BCS against saline, marine and freeze-thaw environments should be examined prior to design.

3.4. Key criteria for design of negative carbon components

Durability against harsh environments should be examined under specific environmental conditions. Some aspects of the performance of BCS in regular environments should likewise be studied, including waterproofing, fireproofing and heat-isolation. Improved waterproofness can be implemented using an external coating/membrane and adjusting integral mixing [34]. The fireproofness of BCS also alters when the external coating or mix proportion is modified [35]. Modifying the integral mix of negative carbon concrete is therefore a reasonable solution, whereby water- and fire-proofness are improved to different extents by adding various compositions of mineral admixture. The heat insulation effect of BCS is generally superior to that of OPC because embedded CO_2 creates a porous structure in concrete and reduces thermal conductivity [36]. The aforementioned aspects should be fully studied and treated as key criteria guiding design.

3.5. Crack control design of non-structural components

Different to the crack control design of concrete material, measures controlling cracks in negative carbon components mainly focus on structural constraint and force conditions, rather than concrete mix proportion or optimized curing treatment [37]. For critical locations in a component, such as demountable joints and variable sections, concrete is subject to different degrees of constraint [33]. The corresponding stress states are thus different, which is useful when considering specific anti-crack strategies. Nevertheless, the load force and restraint force for non-structural components are less high than those for structural components [38]. Similar strategies can be adopted to control the crack width of non-structural members to conform with stipulations in code, however.

3.6. Applications of BCS

While BCS is highly accordant with the “negative carbon” concept, its mechanical properties are unsatisfactory compared with the performance of RC. It can nevertheless still be used in projects as a competitive construction material, to lower carbon footprint. Façades represent one application scenario of BCS. As façades require the properties of low density and good thermal insulation [39], BCS satisfies these requirements. Meanwhile, ideal heat insulation can reduce internal building temperature variation and thus save energy. The other application scenario concerns partition walls, which also demand the use of lightweight concrete with heat insulation [40]. The $MgCO_3$ admixture blended in concrete provides additional fire-resistance to partition walls. CO_2 foam BCS can also improve sound insulation performance. These functionalities make BCS the better choice for application to non-structural components.

4. Integral design to further reduce carbon emissions through life cycle

4.1. Basic functions of integral design

Rigorous design is required to minimize the carbon footprint of a whole project; the three bottom-lines of mechanical behavior, durability and sustainability should all be included in every design. In addition, the range of study should be extended to the whole life cycle of a project [41] since a cradle-to-grave investigation can not only consider short- and long-term structural behaviors, but also calculate carbon emission values during different phases and the net carbon footprint of the project.

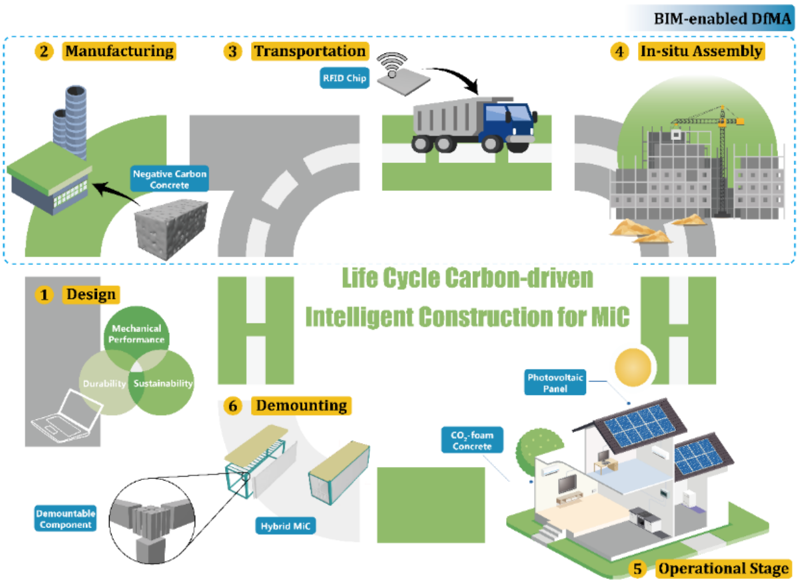

Fig. 3. Integral design for lowering life cycle carbon footprint.

During the durability calculation stage, environmental conditions in the project location should be evaluated. Certain common indices should be particularly considered: CO_2 concentration, temperature and humidity. These items directly influence the degradation of structural components [30] and are controlled by ventilation, heating and air conditioning equipment, all of which consume energy and indirectly release CO_2. Moreover, permeability is a critical parameter controlling durability.

During sustainability planning, carbon emission is generally served as a representative index [42]. The carbon footprint belonging to different elements of the life cycle of project can be measured using sensors. Based on sensor-collected data, the dynamic management of energy consumption plays an important role in optimizing carbon emissions from construction to demolition.

4.2. Integrated building information modelling (IBIM)

When it comes to designing a negative carbon-oriented construction project, collaborative design optimizing different aspects of performance is more challenging than single-aspect design. BIM is a powerful tool by which to achieve integrated design because multi-disciplinary and multi-dimensional information can be integrated and superimposed in one BIM model. To realize negative carbon throughout the whole life cycle, existing BIM technologies must be further updated, as shown in Fig. 3.

Firstly, mechanical calculation should be included in traditional BIM software programs. A novel 4D-BIM concept has been proposed for the purpose of the functional enrichment of BIM 1.0 [41], allowing a combination between structural mechanical calculation and information collection. Secondly, the Internet of things (IoT) provides data to BIM for model update and dynamic decision-making. Recent research has dabbled with the idea of incorporating IoT with BIM [41]. RFID and GPS are used to capture changes in the real world. The results demonstrate that IoT-enabled BIM is beneficial for the real-time management of projects, an idea which is likely transferable to the management of carbon footprint.

Thirdly, a BIM model should cover the whole life cycle. The life cycle of a project generally includes design, manufacturing, transportation, in-situ assembly, the operational stage and demounting/demolition. Integration of all these stages into one model is difficult with existing technology. The industry foundation class (IFC) is an open standard that unifies the data formats of various BIM software programs. By promoting IFC, it is convenient to combine models developed using different software. As for decisions made during each project phase, AI methods embedded within an IoT-enabled BIM model can make decisions automatically, helping contractors optimize management and ensuring a much greener project.

5. Large-scale engineering applications of negative carbon concrete and project delivery approach

Considering large-scale application, work is required in relation to transference to other projects; indeed, the setting of specific negative carbon solutions for typical projects can significantly simplify the design process, once the manufacturing, construction, operation and demolition elements are optimized and regularized for typical projects. The standardization of the whole life cycle project delivery of BCS-MiC is an efficient way in which to reduce carbon footprint on a large scale. Moreover, standardized design and construction can streamline training and certification for consultants and contractors.

One further critical factor relating to the extensive application of negative carbon construction is compilation of local and international policies, codes or standards. Much research is necessary to provide reliable evidence for the development of related codes of practice. From the perspective of certification, developers are more likely to control the carbon footprint of a project when inspired by environmental certifications, including the Building Environmental Assessment Method (BEAM), assessment in Hong Kong, and Leadership in Energy and Environmental Design (LEED) in America.

6. Concluding remarks

This paper reviews current approaches aimed at reducing the carbon footprint of the construction industry, considering four different dimensions. The concept of “negative carbon concrete” is firstly proposed and is assumed to be applied in MiC projects. Key concluding remarks are set out below:

- Negative carbon concrete has been proposed as a promising method by which to reduce the carbon footprint in construction. By CO_2 mineralization and embedding, CO_2 is absorbed into concrete. A combination of these approaches makes negative carbon concrete design feasible.
- BFRP bar-reinforced carbonated SCM concrete (BCS) can increase the durability performance of structures with minimized carbon footprint. The alkaline corrosion problem of BFRP bar can be mitigated by carbonating SCM concrete by way of the reduced pH value of the pore solution.
- Before any application of BCS in MiC components, mechanical properties and durability should be carefully examined. Demountable joints and reusable components can further lower carbon footprint over whole life cycles.
- AI-based MOOP methods are helpful to balance the mechanical performance, durability, sustainability and cost of a MiC building at the design stage. IoT-enabled IBIM can achieve the dynamic management of a project.
- The large-scale application of BCS is a promising solution by which to achieve regional carbon neutralization in the construction industry. The standardization of life cycle project delivery and green certification is pivotal when considering negative carbon MiC.

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References

[1] C. Xi and S.J. Cao, "Challenges and Future Development Paths of Low Carbon Building Design: A Review," Buildings, 12 (2022) 163, doi: 10.3390/buildings12020163.

[2] P. Yang, S. Peng, N. Benani, L. Dong, X. Li, R. Liu, and G. Mao, "An integrated evaluation on China's provincial carbon peak and carbon neutrality," Journal of Cleaner Production, 377 (2022) 134497, doi: 10.1016/j.jclepro.2022.134497.

[3] P. Wu, Y. Song, J. Zhu, and R. Chang, "Analyzing the influence factors of the carbon emissions from China's building and construction industry from 2000 to 2015," Journal of Cleaner Production, 221 (2019) 552–566, doi: 10.1016/j.jclepro.2019.02.200.

[4] N. Garcia-Troncoso, H. Baykara, M.H. Cornejo, A. Riofrio, M. Tinoco-Hidalgo, and J. Flores-Rada, "Comparative mechanical properties of conventional concrete mixture and concrete incorporating mining tailings sands," Case Studies in Construction Materials, 16 (2022) e01031, doi: 10.1016/j.cscm.2022.e01031.

[5] E. Batuecas, I. Ramón-Álvarez, S. Sánchez-Delgado, and M. Torres-Carrasco, "Carbon footprint and water use of alkali-activated and hybrid cement mortars," Journal of Cleaner Production, 319 (2021) 128653, doi: 10.1016/j.jclepro.2021.128653.

[6] G. Hammond and C. Jones, "Inventory of carbon & energy: ICE," Sustainable Energy Research Team, Department of Mechanical Engineering, 2008.

[7] W. Pan and C.K. Hon, "Briefing: Modular integrated construction for high-rise buildings," Proceedings of the Institution of Civil Engineers - Municipal Engineer, 173 (2018) 64–68, doi: 10.1680/jmuen.18.00028.

[8] M.C.G. Juenger, R. Snellings, and S.A. Bernal, "Supplementary cementitious materials: New sources, characterization, and performance insights," Cement and Concrete Research, 122 (2019) 257–273, doi: 10.1016/j.cemconres.2019.05.008.

[9] J. Liu, C.Yu, X. Shu, Q. Ran, and Y. Yang, "Recent advance of chemical admixtures in concrete," Cement and Concrete Research, 124 (2019) 105834, doi: 10.1016/j.cemconres.2019.105834.

[10] O. Ortiz, F. Castells, and G. Sonnemann, "Sustainability in the construction industry: A review of recent developments based on LCA," Construction and Building Materials, 23 (2009) 28–39, doi: 10.1016/j.conbuildmat.2007.11.012.

[11] J.M. Matter, M. Stute, S.Ó. Snæbjörnsdottir, E.H. Oelkers, S.R. Gislason, E.S. Aradottir, B. Sigfusson, I. Gunnarsson, H. Sigurdardottir, E. Gunnlaugsson, G. Axelsson, H.A. Alfredsson, D. Wolff-Boenisch, K. Mesfin, D.F. de la R. Taya, J. Hall, K. Dideriksen, and W.S. Broecker, "Rapid carbon mineralization for permanent disposal of anthropogenic carbon dioxide emissions," Science, 352 (2016) 1312–1314, doi: 10.1126/science.aad8132.

[12] N. Zhang, Y.E. Chai, R.M. Santos, and L. Šiller, "Advances in process development of aqueous CO_2 mineralisation towards scalability," Journal of Environmental Chemical Engineering, 8 (2020) 104453, doi: 10.1016/j.jece.2020.104453.

[13] Z. Yi, T. Wang, and R. Guo, "Sustainable building material from CO_2 mineralization slag: Aggregate for concretes and effect of CO_2 curing," Journal of CO_2 Utilization, 40 (2020) 101196, doi: 10.1016/j.jcou.2020.101196.

[14] A.A. Ghabban, A.B.A. Zubaidi, M. Jafar, and Z. Fakhri, "Effect of Nano SiO_2 and Nano $CaCO_3$ on The Mechanical Properties," Durability and flowability of Concrete, IOP Conference Series: Materials Science and Engineering, 454 (2018) 012016, doi: 10.1088/1757-899X/454/1/012016.

[15] C.M. Woodall, N. McQueen, H. Pilorgé, and J. Wilcox, "Utilization of mineral carbonation products: current state and potential," Greenhouse Gases: Science and Technology, 9 (2019) 1096–1113, doi: 10.1002/ghg.1940.

[16] K. Scrivener, F. Martirena, S. Bishnoi, and S. Maity, "Calcined clay limestone cements (LC^3)," Cement and Concrete Research, 114 (2018) 49–56, doi: 10.1016/j.cemconres.2017.08.017.

[17] M. Sabău, D.V. Bompa, and L.F.O. Silva, "Comparative carbon emission assessments of recycled and natural aggregate concrete: Environmental influence of cement content," Geoscience Frontiers, 12 (2021) 101235, doi: 10.1016/j.gsf.2021.101235.

[18] V.W.Y. Tam, A. Butera, K.N. Le, and W. Li, "Utilising CO_2 technologies for recycled aggregate concrete: A critical review," Construction and Building Materials, 250 (2020) 118903, doi: 10.1016/j.conbuildmat.2020.118903.

[19] L. Rosa, V. Becattini, P. Gabrielli, A. Andreotti, and M. Mazzotti, "Carbon dioxide mineralization in recycled concrete aggregates can contribute immediately to carbon-neutrality," Resources, Conservation and Recycling, 184 (2022) 106436, doi: 10.1016/j.resconrec.2022.106436.

[20] A. Raj, D. Sathyan, and K.M. Mini, "Physical and functional characteristics of foam concrete: A review," Construction and Building Materials, 221 (2019) 787–799, doi: 10.1016/j.conbuildmat.2019.06.052.

[21] N.V. Rao and T. Meena, "A review on carbonation study in concrete," IOP Conference Series: Materials Science and Engineering, 263 (2017) 032011, doi: 10.1088/1757-899X/263/3/032011.

[22] N. Garg and S. Shrivastava, "Environmental and Economic Comparison of FRP Reinforcements and Steel Reinforcements in Concrete Beams Based on Design Strength Parameter," UKIERI Concrete Congress, Mar. 2019.

[23] J. Liu, N. Li, M. Chen, J. Yang, B. Long, and Z. Wu, "Durability of basalt fiber-reinforced polymer bars in wet-dry cycles alkali-salt corrosion," Science and Engineering of Composite Materials, 26 (2019) 43–52, doi: 10.1515/secm-2018-0030.

[24] X. Wang, J. Shi, J. Liu, L. Yang, and Z. Wu, "Creep behavior of basalt fiber reinforced polymer tendons for prestressing application," Materials & Design, 59 (2014) 558–564, doi: 10.1016/j.matdes.2014.03.009.

[25] E. Nepomuceno, J. Sena-Cruz, L. Correia, and T. D'Antino, "Review on the bond behavior and durability of FRP bars to concrete," Construction and Building Materials, 287 (2021) 123042, doi: 10.1016/j.conbuildmat.2021.123042.

[26] M.W. Wei, J.H. Xie, H. Zhang, and J.L. Li, "Bond-slip behaviors of BFRP-to-concrete interfaces exposed to wet/dry cycles in chloride environment," Composite Structures, 219 (2019) 185–193, doi: 10.1016/j.compstruct.2019.03.049.

[27] A. Siddika, Md.A.A. Mamun, R. Alyousef, and Y.H.M. Amran, "Strengthening of reinforced concrete beams by using fiber-reinforced polymer composites: A review," Journal of Building Engineering, 25 (2019) 100798, doi: 10.1016/j.jobe.2019.100798.

[28] M. Noël and K. Soudki, "Estimation of the crack width and deformation of FRP-reinforced concrete flexural members with and without transverse shear reinforcement," Engineering Structures, 59 (2014) 393–398, doi: 10.1016/j.engstruct.2013.11.005.

[29] H. Hamilton III and C. Dolan, “Durability of FRP reinforcements for concrete,” Progress in Structural Engineering and Materials, 2 (2000) 139–145.
[30] Z. Wang, X.L. Zhao, G. Xian, G. Wu, R.K. Singh Raman, S. Al-Saadi, and A. Haque, “Long-term durability of basalt- and glass-fibre reinforced polymer (BFRP/GFRP) bars in seawater and sea sand concrete environment,” Construction and Building Materials, 139 (2017) 467–489, doi: 10.1016/j.conbuildmat.2017.02.038.
[31] L. AlNajmi and F. Abed, “Evaluation of FRP Bars under Compression and Their Performance in RC Columns,” Materials, 13 (2020) 4541, doi: 10.3390/ma13204541.
[32] R. Shamass and K.A. Cashell, “Experimental investigation into the flexural behaviour of basalt FRP reinforced concrete members,” Engineering Structures, 220 (2020) 110950, doi: 10.1016/j.engstruct.2020.110950.
[33] D. Figueira, A. Ashour, G. Yıldırım, A. Aldemir, and M. Şahmaran, “Demountable connections of reinforced concrete structures: Review and future developments,” Structures, 34 (2021) 3028–3039, doi: 10.1016/j.istruc.2021.09.053.
[34] N.Z. Muhammad, A. Keyvanfar, M.Z. Abd. Majid, A. Shafaghat, and J. Mirza, “Waterproof performance of concrete: A critical review on implemented approaches,” Construction and Building Materials, 101 (2015) 80–90, doi: 10.1016/j.conbuildmat.2015.10.048.
[35] S.J. Choi, S.H. Kim, S.J. Lee, and J.P. Won, “Mix proportion of eco-friendly fireproof high-strength concrete,” Construction and Building Materials, 38 (2013) 181–187, doi: 10.1016/j.conbuildmat.2012.07.103.
[36] E.A. Barteneva, M.A. Ylesin, N.A. Mashin, and D.V. Dubrov, “Improvement of Heat-Insulating Properties of Foam Concrete by Means of Mineral Additives,” Key Engineering Materials, 771 (2018) 31–36, doi: 10.4028/www.scientific.net/KEM.771.31.
[37] X. Chen and J. Xu, “Study on the Comprehensive Method of Crack Control in Engineering Structure,” Journal of Physics: Conference Series, 1574 (2020) 012033, doi: 10.1088/1742-6596/1574/1/012033.
[38] M. Matsubayashi, Y. Takase, and M. Mizoguchi, “Shear strength and cracking behavior of reinforced concrete nonstructural walls,” Journal of Asian Architecture and Building Engineering, 21 (2022) 380–392, doi: 10.1080/13467581.2020.1838290.
[39] T. Adams, A. Vollpracht, J. Haufe, L. Hildebrand, and S. Brell-Cokcan, “Ultra-lightweight foamed concrete for an automated facade application,” Magazine of Concrete Research, 2019, doi: 10.1680/jmacr.18.00272.
[40] N.M. Zahari, I.A. Rahman, A.M.A. Zaidi, and A. Mujahid, “Foamed concrete: potential application in thermal insulation,” Malaysian Technical Universities Conference on Engineering and Technology, Jun. 2009.
[41] C.Z. Li, F. Xue, X. Li, J. Hong, and G. Shen, “An Internet of Things-enabled BIM platform for on-site assembly services in prefabricated construction,” Automation in Construction, 2018, doi: 10.1016/J.AUTCON.2018.01.001.
[42] M. Zimmermann, H.J. Althaus, and A. Haas, “Benchmarks for sustainable construction: A contribution to develop a standard,” Energy and Buildings, 37 (2005) 1147–1157, doi: 10.1016/j.enbuild.2005.06.017.

INTEGRATED CONCRETE MIX DESIGN WITH SUSTAINABILITY, COST AND DURABILITY BASED ON ARTIFICIAL INTELLIGENCE

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Abstract

Concrete production accounts for a substantial portion of global CO2 emission. One of possible ways to reduce the carbon footprint of concrete is to optimize the concrete mix design approach. This paper investigates the integration of sustainability, cost and durability performance with concrete mix based on artificial neural network. Carbonation-induced corrosion resistance is used for characterizing the durability performance of concrete mix. A dataset on natural carbonation coefficient, compressive strength and concrete mix design of concretes with various supplementary cementitious materials (SCMs) is established. An artificial neural network is trained, and used in designing a concrete mix with optimized sustainability, cost and durability performances given a target compressive strength. The results show that the artificial intelligence is promising in integrated concrete mix design with favorable sustainability, cost and durability performances.

Keywords: artificial intelligence, concrete mix design, cost, durability, sustainability

1. Introduction

Concrete mix, primarily composed of cement, aggregates, and water, plays a significant role in greenhouse gas (GHG) emissions. Cement production, which involves the calcination of limestone, is responsible for roughly 8% of global CO_2 emissions [1]. These emissions stem from both the energy-intensive manufacturing process and the chemical reactions during calcination. Mitigating concrete's environmental impact requires innovative solutions, such as alternative cementitious materials, optimization of concrete mix design, and improved production practices to reduce the industry's carbon footprint. Young et. al. [2] compared the uses of decision tree, supporting vector machine and artificial neural network on reducing the carbon footprint and cost of concrete. They concluded that all of the machine learning algorithms are able to predict the compressive strength with optimized cost and sustainability performances. Under CO_2 penetration and chloride ingression, concrete will degrade due to the corrosion of steel reinforcement [3]. This has been characterized as durability problem. Chen et. al. [4] developed a hybrid machine learning model to predict the durability performance of concrete. Unfortunately, no papers have investigated the use of artificial neural network on optimizing the cost, sustainability, durability and compressive strength of concrete.

This paper aims to integrating the sustainability, cost and durability performances with compressive strength in concrete mix design process with the use of artificial intelligence. An artificial neural network was built and trained by collecting 909 concrete mix data in existing literatures. A framework was proposed to optimize the sustainability, cost and durability performances upon a specified compressive strength.

2. Development of artificial neural network

2.1. Data collection

Databases are crucial in neural network modeling. A good dataset enables the neural networks to learn patterns, relationships, and features by exposing them to diverse examples. Consequently, a robust database fosters better generalization, improved accuracy, and enhanced performance in real-world applications. Additionally, databases facilitate the benchmarking and comparison of different models, thereby promoting continuous advancements in the field of neural network research and development.

This paper assembles a dataset by collecting 909 concrete mix data in existing literatures as shown in Table 1. All of the literatures as shown in Table 1 provide a detailed description on the concrete mix design and carbonation-induced durability performance of concrete mix, since this paper focuses on the integration of durability performance in concrete mix optimization.

Table 1 List of literatures for extraction of natural carbonation coefficients data in this study

Number	Author and year of publication	Title
1	Vu 2019	Impact of different climates on the resistance of concrete to natural carbonation
2	Yunusa 2014	The effect of materials and micro-climate variations of predictions of carbonation rate in reinforced rate in reinforced concrete in the inland environment
3	Bouzoubaa 2010	Carbonation of fly ash concrete: laboratory and field data
4	ZHANG 1985&1990	Natural carbonation of fly ash blended concrete(in Chinese)
5	Jones 2001	Comparison of 2 year carbonation depths of common cement concretes using the modified draft CEN test
6	Sanjuan 2003	Concrete carbonation tests in natural and accelerated conditions
7	Tam 2008	Carbonation of concrete in the tropical environment of Singapore
8	Jia 2010	Research on carbonation characteristics of concrete with large amount of supplementary cementitious materials (in Chinese)
9	Lu 2012	Prediction methodology on durability of fly ash blended concrete under natural environment (in Chinese)
10	Duran 2014	Accelerated and natural carbonation of concretes with internal curing and shrinkage/viscosity modifiers
11	Sundar 2017	Modelling carbonation rates in concretes with similar strength and with and without slag
12	Dhanya 2019	Carbonation and its effect on microstructure of concrete with fly ash and ggbfs
13	Dhir 1989	Near-surface characteristics of concrete: prediction of carbonation resistance
14	Khunthongkeaw 2006	A study on carbonation depth prediction for fly ash concrete
15	Roziere 2009	A performance based approach for durability of concrete exposed to carbonation
16	Leemann 2015	Relation between carbonation resistance, mix design and exposure of mortar and concrete
17	Leemann 2016	Carbonation of concrete: the role of CO2 concentration, relative humidity and CO2 buffer capacity
18	Sundar 2022	Carbonation model for concretes with fly ash, slag, and limestone calcined clay - using accelerated and five - year natural exposure data
19	Akli 2022	Quantification of CO2 uptake of concretes with mineral additions after 10-year natural carbonation
20	Lollini 2021	Carbonation of blended cement concretes after 12 years of natural exposure
21	Rivera 2021	Performance of Ground Granulated Blast-Furnace Slag and Coal Fly Ash Ternary Portland Cements Exposed to Natural Carbonation
22	Zhao 2021	Performance of GGBS Cement Concrete under Natural Carbonation and Accelerated Carbonation Exposure
23	Ribeiro 2018	Performance of concrete exposed to natural carbonation: Use of the k-value concept

2.2. Input and output parameters of neural network

Table 2 describes the parameters to be inputted into the artificial neural network in this paper. There are three types of input parameters as shown in Table 2. The first type of input parameters is used to characterize the concrete mix constituents. The second and third types of input parameters are related to the concrete curing process and environmental conditions of concrete after hardening, which have been found to significantly affect the carbonation coefficient of concrete [5, 6].

Table 2 Input parameters of neural network training

Classification	Input parameters	Unit
Concrete mix constituents	CEM I 42.5 N OPC content	kg/m^3
	CEM I 52.5 N OPC content	kg/m^3
	Class C fly ash content	kg/m^3
	Class F fly ash content	kg/m^3
	GGBS content	kg/m^3
	Silica fume content	kg/m^3
	Water content	kg/m^3
	Maximum aggregate size	kg/m^3
	Coarse aggregate content	kg/m^3
	Fine aggregate content	kg/m^3
Concrete curing	Curing method (Air/Moist/Submerged/Sealed)	N.A.
	Curing temperature	Celsius degree
	Curing humidity	%
	Curing day	Day
Exposure environment	Exposure environment (Indoor, Outdoor sheltered, Outdoor unsheltered)	N.A.
	Annual average CO_2 concentration	%
	Annual average humidity	%
	Annual average temperature	%
	Annual wetting times/rainy days of exposed environment	Day
	Annual average precipitation	mm

The output parameters of the artificial neural network are 28-day compressive strength of 150 mm cubes and natural carbonation coefficient.

2.3. Neural network training

An artificial neural network is trained by the collected dataset as described above. Through model tuning, the optimized hyperparameters are listed in Table 3. Activation functions are Rectified Linear Unit (ReLU) and linear for hidden layers and output layer respectively. Loss function is mean absolute error. Optimizier is Adam. The numbers of data used for training and validation are in the ratio of 0.8:0.2. Both the input and output parameters are scaled by standard scaler.

Table 3 Tunned hyperparameters of artificial neural network

Parameter	Value
Number of hidden layers	5
Number of nodes	32
Epochs	100
Batch size	2

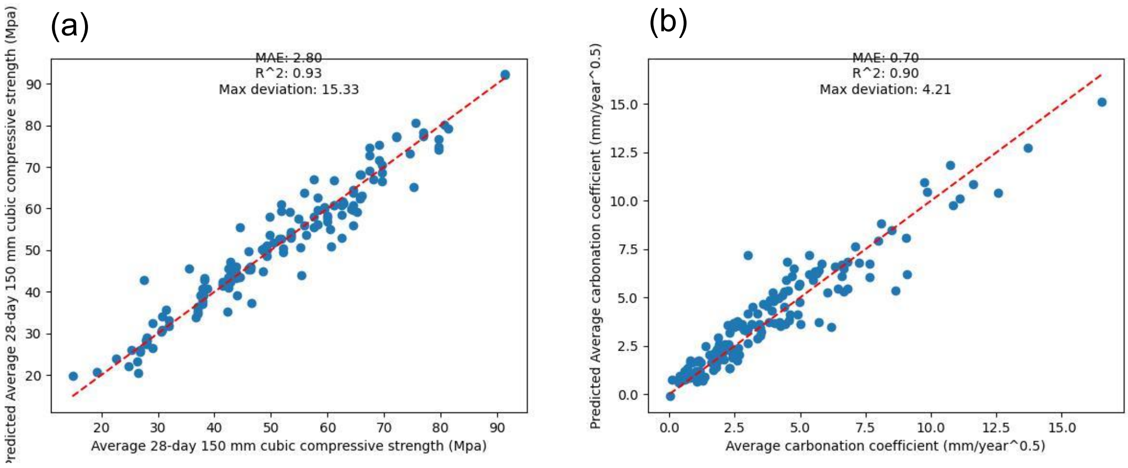

Fig. 1 Validation results of trained artificial neural network. (a) 28-day 150 mm cubic compressive strength and (b) average carbonation coefficient

Fig. 1 shows the validation results on the validation dataset of the artificial neural network in this paper. The R-squared coefficients are 0.93 and 0.90 respectively as shown in Fig. 1 (a) and (b). One may conclude that the neural network is well-trained and able to predict the 28-day compressive strength of 150 mm cube and natural carbonation coefficient under given input parameters.

2.4. Algorithm of concrete mix design

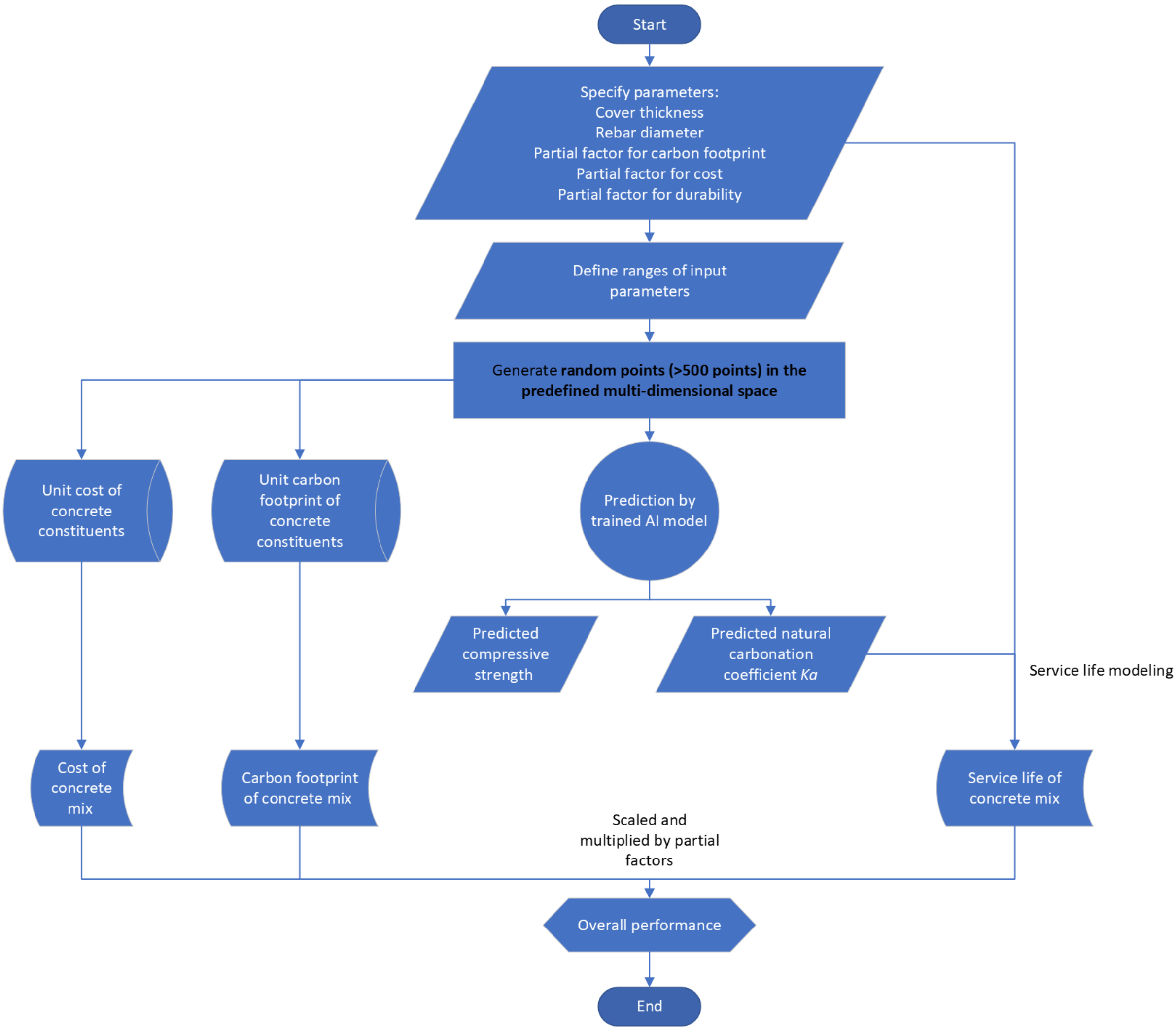

Fig. 2 Flow chart of concrete mix deisgn considering cost, carbon footprint, durability and compressive strength

In order to integrate the cost, sustainability and durability performances with compressive strength of concrete, an optimization framework has been proposed as shown in Fig. 2. The optimization starts with specifying five parameters, namely cover thickness of concrete component, rebar diameter of reinforced concrete, partial factors of sustainability, cost and durability performances of concrete mix. This is followed by defining the ranges of input parameters as shown in Table 4. The constraints listed in Table 4 construct a high-dimensional bounding box, in which a large amount of data points with different combinations of input parameters as shown in Table 2 are randomly generated.

As shown in Fig. 3, one may calculate the cost and carbon footprint of concrete mix based on the concrete constituents and the unit cost and unit carbon footprint of concrete constituents as shown in Table 5. Given the input parameters of the random points, the 28-day compressive strength of 150 mm cube and natural carbonation coefficient of the concrete mixes can be predicted by the trained artificial neural network. The predicted carbonation coefficient K_a, the predefined cover thickness *c* and rebar diameter *d* are used to predict the service life of the reinforced concrete component under specified exposure condition [5, 7, 8]:

$$t_s = (4300d+221499c^2-2781c+45)K_a^{2.49d-7.20c-1.39} \quad \text{(XC3ID)}$$
$$t_s = (3354d+191371c^2-633c-0.9)K_a^{0.35d-6.58c-1.46} \quad \text{(XC3OD)}$$
$$t_s = (1361d+544414c^{2.44}-5.8)K_a^{-2.00} \quad \text{(XC4OD)}$$

The above equations for calculating the service life of carbonated reinforced concrete component are previous research results of the authors. More details can be found in [5].

It should be noted that the obtained cost, carbon footprint and service life of concrete mixes must be scaled into [0,1] for consistency. The obtained service lives are scaled by MinMaxScaler in Python while the obtained cost and carbon footprint are scaled by the same scaler and followed by an inversion processing, so that the scaled value of 1 indicates the point with best performance and the scaled value of 0 indicates the point with worst performance. Upon scaling, the overall performance index can be obtained by the following equation:

$$I = I_c PF_c + I_{cf} PF_{cf} + I_d PF_d$$

where I is the overall performance, I_c is the scaled value of cost, PF_c is the partial factor of cost, I_{cf} is the scaled value of carbon footprint, PF_{cf} is the partial factor of carbon footprint, I_d is the scaled value of durability (service life), PF_d is the partial factor of durability (service life).

The values of the partial factors are subject to the following equation:

$$PF_c + PF_{cf} + PF_d = 1$$

The overall performance I of a specific concrete mix can be used to evaluate the concrete mix based on the predefined partial factors, which are used to characterize the relevant importance of cost, carbon footprint and durability performances.

Table 4 Ranges of input parameters for artificial neural network modelling

Parameter	Lower bound	Upper bound
Cementitious material content	200	200
water/binder ratio	0.3	0.3
Replacement level of fly ash	0	0
Replacement level of GGBS	0	0
Replacement level of SF	0	0
Water content	130	130
Maximum coarse aggregate size	20	20
Coarse aggregate content	700	700
Fine aggregate content	700	700
Paste ratio	0.2	0.2
Coarse aggregate ratio	0.4	0.4
Density	2200	2200
Cementitious material content	200	200

Table 5 Carbon footprint and cost for concrete mix constituents

Parameter	Carbon foot print (kg/kg)	Cost (HKD/kg)
CEM I 42.5N ordinary Portland Cement	0.67	0.821
CEM I 52.5N ordinary Portland Cement	0.82	0.931
Class C Fly ash	0	0.31
Class F Fly ash	0	0.165
Slag	0	0.3
Silica fume	0	3

Water	0.000674	0.00711
Coarse aggregate	0.0144	0.113
Fine aggregate	0.01734	0.307

3. Results and discussions

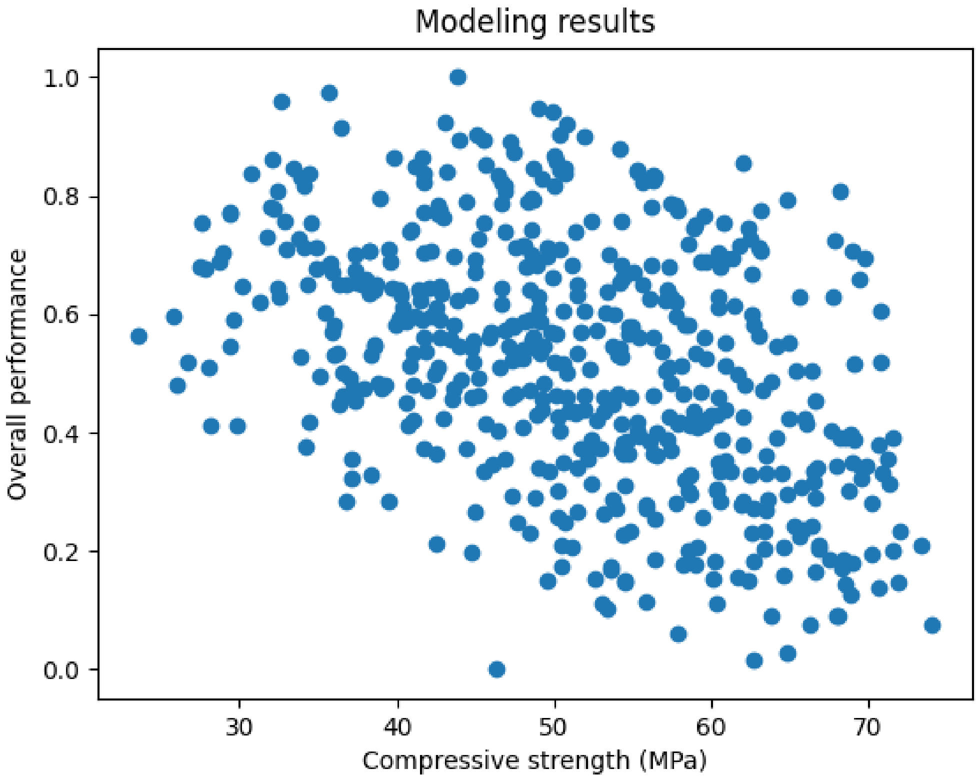

Fig. 4 Results of concrete mix design with partial factor of sustainability =1, other two factors equal to 0.

Fig. 4 present the optimization result by using the proposed framework as shown in Section 2, in which the relationship of overall performance and compressive strength of concrete mixes is displayed. The partial factor of sustainability is 1, while the partial factors of cost and durability are 0. In this set of partial factors, a concrete mix with lowest carbon footprint will be considered as the optimal result. As indicated by Fig. 4, the compressive strength of such mix is 42 Mpa. One may also find that there is a trend in which the overall performance decreases with the increase in compressive strength, which is consistent with the results in [6]. In other words, one may lower the compressive strength of concrete to reduce the carbon footprint of concrete by increasing the water/binder ratio (mostly due to decreased binder content).

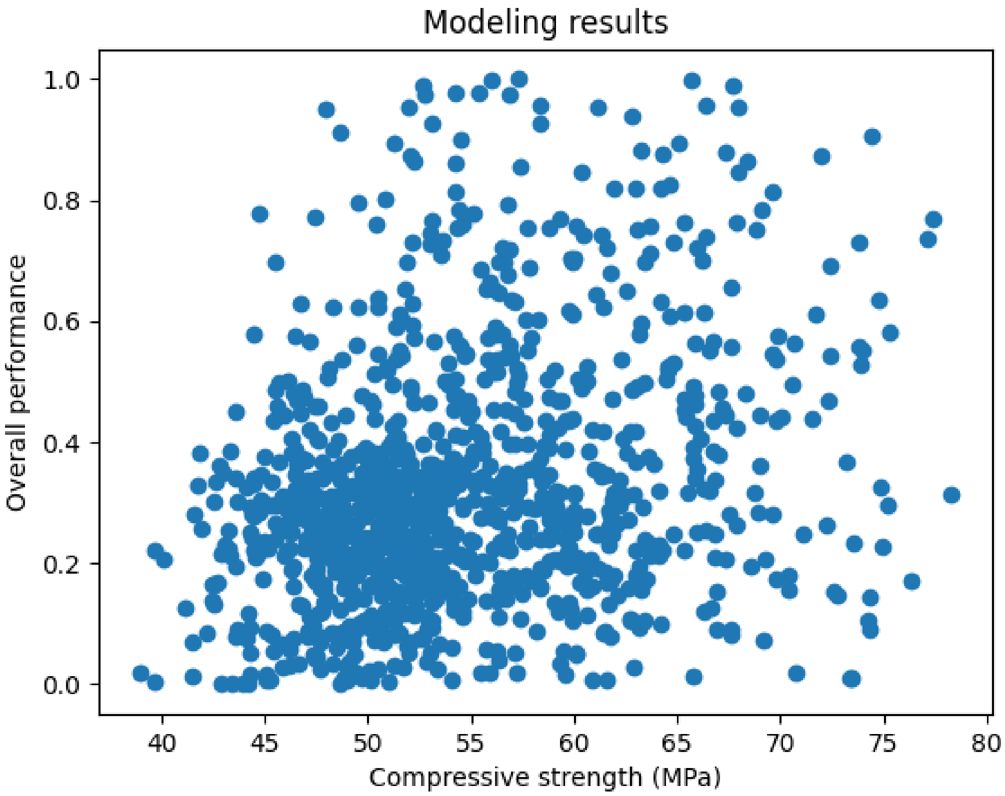

Fig. 5 Results of concrete mix deisgn with partial factor of durability =1, other two factors =0.

Fig. 5 present the optimization result by using the proposed framework as shown in Section 2 with the partial factor of sustainability as 1 and the partial factors of cost and durability as 0. In this set of partial factors, a concrete mix with highest durability will be considered as the optimal result. One may also find that there is a trend in which the overall performance increases with the increase in compressive strength, which is consistent with the results in [6, 9]. In other words, one may increase the compressive strength of concrete to prolong the service life of concrete by decreasing the water/binder ratio (mostly due to increased binder content).

4. Conclusions

The aim of this research paper is to explore how the integration of sustainability, cost, and durability performance can be achieved in concrete mix using artificial neural network technology. The durability performance of the concrete mix is assessed using carbonation-induced corrosion resistance. A comprehensive dataset is compiled that includes the natural carbonation coefficient, compressive strength, and concrete mix design of concretes with various supplementary cementitious materials (SCMs). The artificial neural network is then trained on this dataset to design a concrete mix that optimizes sustainability, cost, and durability performances while achieving a target compressive strength. The study demonstrates that artificial intelligence has great potential in the development of concrete mix designs that offer favorable sustainability, cost, and durability performances. One may increase the compressive strength of concrete to prolong the service life of concrete by decreasing the water/binder ratio while decrease the compressive strength of concrete to improve the sustainability performance of concrete by increasing water/binder ratio.

References

[1] K.-H. Yang, Y.-B. Jung, M.-S. Cho, and S.-H. Tae, "Effect of supplementary cementitious materials on reduction of CO2 emissions from concrete," *J. Clean. Prod.,* vol. 103, pp. 774-783, 2015, doi: 10.1016/j.jclepro.2014.03.018.

[2] B. A. Young, A. Hall, L. Pilon, P. Gupta, and G. Sant, "Can the compressive strength of concrete be estimated from knowledge of the mixture proportions?: New insights from statistical analysis and machine learning methods," *Cem. Concr. Res.,* vol. 115, pp. 379-388, 2019, doi: 10.1016/j.cemconres.2018.09.006.

[3] L. Bertolini, B. Elsener, P. Pedeferri, E. Redaelli, and R. Polder, *Corrosion of steel in concrete*. Wiley Online Library, 2013.

[4] Z. Chen, J. Lin, K. Sagoe-Crentsil, and W. Duan, "Development of hybrid machine learning-based carbonation models with weighting function," *Constr. Build. Mater.,* vol. 321, 2022, doi: 10.1016/j.conbuildmat.2022.126359.

[5] L. Chen, "Corrosion rate of macrocell corrosion in reinforced concrete and service life modeling of carbonated concrete containing supplementary cementitious materials," Ph.D., Ph.D. Thesis, University of Hong Kong, Hong Kong, 2022.

[6] S. von Greve-Dierfeld *et al.*, "Understanding the carbonation of concrete with supplementary cementitious materials: a critical review by RILEM TC 281-CCC," *Mater. Struct.,* vol. 53, no. 6, 2020, doi: 10.1617/s11527-020-01558-w.

[7] P. F. Marques, C. Chastre, and Â. Nunes, "Carbonation service life modelling of RC structures for concrete with Portland and blended cements," *Cem. Concr. Compos.,* vol. 37, pp. 171-184, 2013, doi: 10.1016/j.cemconcomp.2012.10.007.

[8] *Concrete. Specification, performance, production and conformity*, 2013.

[9] M. Stefanoni, U. Angst, and B. Elsener, "Corrosion rate of carbon steel in carbonated concrete – A critical review," *Cem. Concr. Res.,* vol. 103, pp. 35-48, 2018, doi: 10.1016/j.cemconres.2017.10.007.

DESIGN AND NATURAL MATERIALS – INNOVATIVE APPROACHES FOR A SUSTAINABLE FUTURE ARCHITECTURE AND STRUCTURAL ENGINEERING

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Abstract

Perceptible limitations of resources, energy and agglomerations of waste cause modern societies to consider and expand research on sustainable and natural principles. In this context, the building construction sector, with its large impact on material consumption and landfilling, requires special attention and consideration. Strategies may include: using recyclable materials, reducing material waste and entropy, and using bio-based materials that can be returned to the natural material cycle without any treatment or separation processes.

The paper gives an insight into the design and elaboration of lightweight metal sheet structures, approaches to the use of raw wood for structures and structural purposes, and the material design of mycelium composite components for construction purposes. Parametric design tools enable the control of complex geometries both at the general and detailed level of metal sheet shells and folded plate structures. New approaches like Off-Knot-Design combined with digital taxonomy and parametric tools provide a new way to design frame, truss, or beam-like structures from raw wood parts. Material design principles and the use of symbiotic biological properties help develop fungus and wood composites that can be disposed without further post-processing. The shown approaches demonstrate how well-known materials such as metal sheets and old materials such as wood lead to innovative sustainable solutions through interdisciplinary knowledge combined with computer algorithms and tools.

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Keywords: metal sheet lightweight structures, self-tapping screws, mycelium composites, off-knot design, parametrical tools, raw wood design.

1. Approaches for a sustainable building design and building-construction

For a particular sustainable building design based on a minimized use of material or based on natural materials special technical approaches have to be considered and traced. For building purposes on one hand material must be available in mass dimensions and on the other hand, concerning the end of use, material should be totally recyclable or directly be brought back to the natural cycle. Materials must not be too refined just as much it is required due to production premises and processing. Materials which are just suitable at end of use for downcycling, like concrete and other artificial stone products, should be limited in use. Similarly, plastics, made from fossil oil, may not accepted as sustainable building materials. Wood as one of the oldest natural building materials in the northern climate zones of the earth was affordable to win and became typical for the rural and town architecture in these regions. Due to its insufficient fire resistance and resistance against biological attacks man started coating of timber elements, using chemicals to come over these problems. Chemically treated wood may not be brought back to nature without spoiling natural resources of soil and water. The technical strategy must include the development of biobased coating and protecting systems, in order to create fully bio-degradable timber-components, to be stored in nature without empoisoning it. And another part of a future sustainable technical strategy should be the development of biobased materials to be used as voluminous material producing walls, panels, insulation devices like e.g. mycelium-composites, starch-based composites and similar substances.

Steel, another common material in building construction, is, compared to others, a nearly fully recyclable one. It is strong with high performance in strength and load-bearing capacity and, therefore, preferably applicable to lightweight structures. Traditional steel construction is based on building-kit-like longitudinal element sections like I-, U- or hollow-sections and typed nuts-and-bolts joining details. Plate-girder beams, box girders, and spheric shells made from doubly curved steel plates, welded together, form contiguous building components for bridges and containers. Modern steel construction is based on individualized sheet-metal elements, used in the automotive and aeronautic design, where weight minimization is essential, and in building construction, where resource-saving is crucial. Sheet-metal element design allows the combination of structural and covering purposes and the creation of integrated stiff and stable structures.

2. Steel-Lightweight-Structures

Frei Otto (1925-2015) was one of the pioneers of tensile-loaded lightweight structures. Jean Prouvé (1901-1984) and Hugo Junkers (1859-1935) were pioneers in using sheet metal for buildings and housings. Concerning sheet-metal structures the introduction of tessellation systems for segmentation is essential to achieve structural efficiency and to allow prefabrication. Orthogonal structures out from sheet metal will be based on modular systems, 3D-bended folded or shell-like structures are based on topological order systems.

2.1. Self-supporting lightweight-building system from sheet-metal

Advanced CAD systems and parametric design tools enable us to describe any individualized three-dimensional curved shape and develop and detail it within the computer environment. Appropriate methods for subdividing ensure the realization of the virtual models of free-formed buildings. Modular order gives place to topological order, where parts agree in their general shape but not in their dimensions. Suitable structural principles for load-bearing sheet-metal structures must be developed [1].

2.2. Prototype 1

The Chair of Structures and Structural Design and the Institute of Metal Forming at Aachen University developed a building system for self-supporting sheet-metal shells and built prototypes to investigate the productional and statical potentials of the construction system as well as their applicability. Based on double-layered Fold-Core-Plates (germ: ‘Faltleichtbauplatten’) with a plane layer connected to a layer of hexagonal pyramids, providing bending capacity in three areal dimensions. The Prototype 1 ‘Flying Carpet’ was developed based on Rhino-Grasshopper-scripts, where the complete geometrical information, also for the production of the individual parts based on Incremental Sheet-Forming (ISF), was extracted [2, 3]. Prototype 1 (see Fig. 1) consists of 140 hexagonal pyramid elements and 319 triangular plates, joined together at the folds by clinching and connecting the two layers with spot-welded threaded bolts and nuts. The whole production of the parts corresponds with a true File-to-Factory-Process.

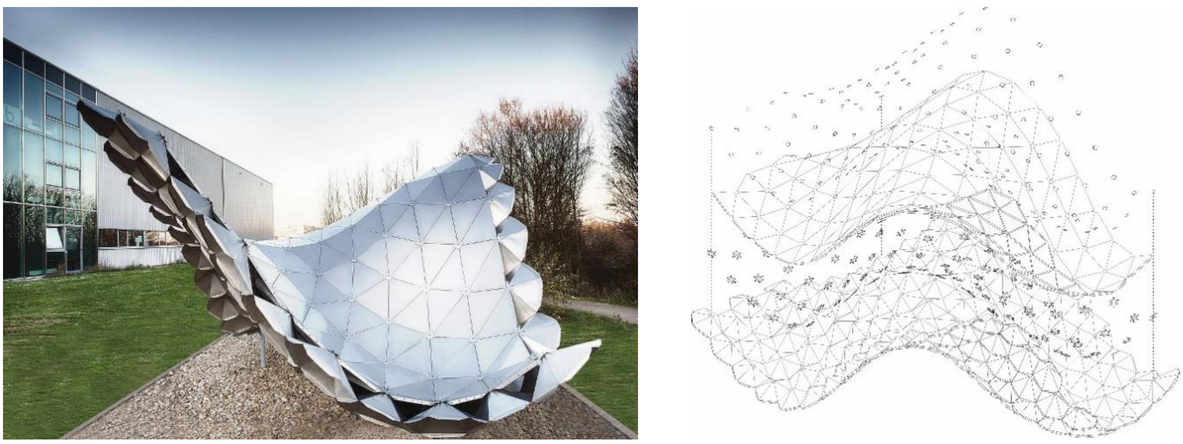

Fig. 1. Prototype 1 based on faceted plane components.

2.3. Prototype 2

As Prototype 1 has faceted surfaces, developing the process onto smooth surfaces was challenging. The ISF -procedure had to be developed and combined with stretch drawing. To extend the range of forms, a simple mold called 'Smart-Die' was introduced, which allowed the realization of smooth, three-dimensional curvature of panels. Instead, joints at the folded edge of the panels were connected by a layered joint, minimizing the joint gap, and supporting the continuity of the overall geometry of the prototype. Punched-in cones into the inner sheet metal take over the shear connection between both layers, replacing the pyramidal layer of the previous prototype [4, 5]. Prototype 2 (see Fig. 2) will soon be presented on the campus of RWTH Aachen as a pavilion.

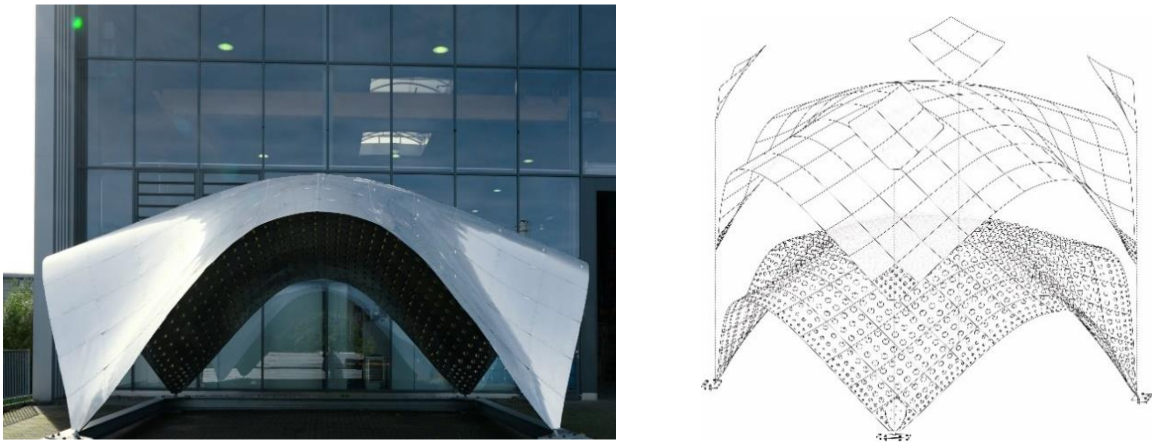

Fig. 2. Prototype 2 based on smooth sheet-metal components.

2.4. Prototype 3

The double-layer construction of the previous prototypes causes a significant effort. For specific purposes, just one layer of steel sheet metal is sufficient, e.g., if just a predominant load case is acting or if a steel-sheet-metal layer is part of a hybrid or composite system combined with a concrete shell above. The one-layer compression loadable membrane system consists of metal sheets with coined in star-like crosses arranged as a regular pattern, preventing local buckling (see Fig. 3) [6]. The inclined stars may overtake the shear connection by tight fit.

Fig. 3. Prototype 3 based on one-layer represents a pattern-coined compression-loadable membrane

3. Wood and natural materials

In the context of sustainability is wood design a very popular material. In the building construction context, it is traditionally applied according to its natural property in longitudinal components or as boards. Modern forms are glue-laminated beams or cross-laminated panels. A systemic disadvantage of wood is its anisotropic strength behaviour with high strength parallel to grain and a relative weakness perpendicular to it, with a negative effect on joints, especially with mechanical fasteners. On the other hand, biodegrading organisms process wood and produce hyphens that provide the ability to join wood parts that can be used for fully bio-based and new composite materials and wood semi-finished products.

Classical timber production is based on a selection of parts of trees like the stem, which causes a huge mass of waste to be processed into wood chips. Using glue, this is further processed to OSB-boards and other glue-based timber composites. Another way to deal with wood as it is grown, raw wood, is to use it as structural elements with minimized refinement.

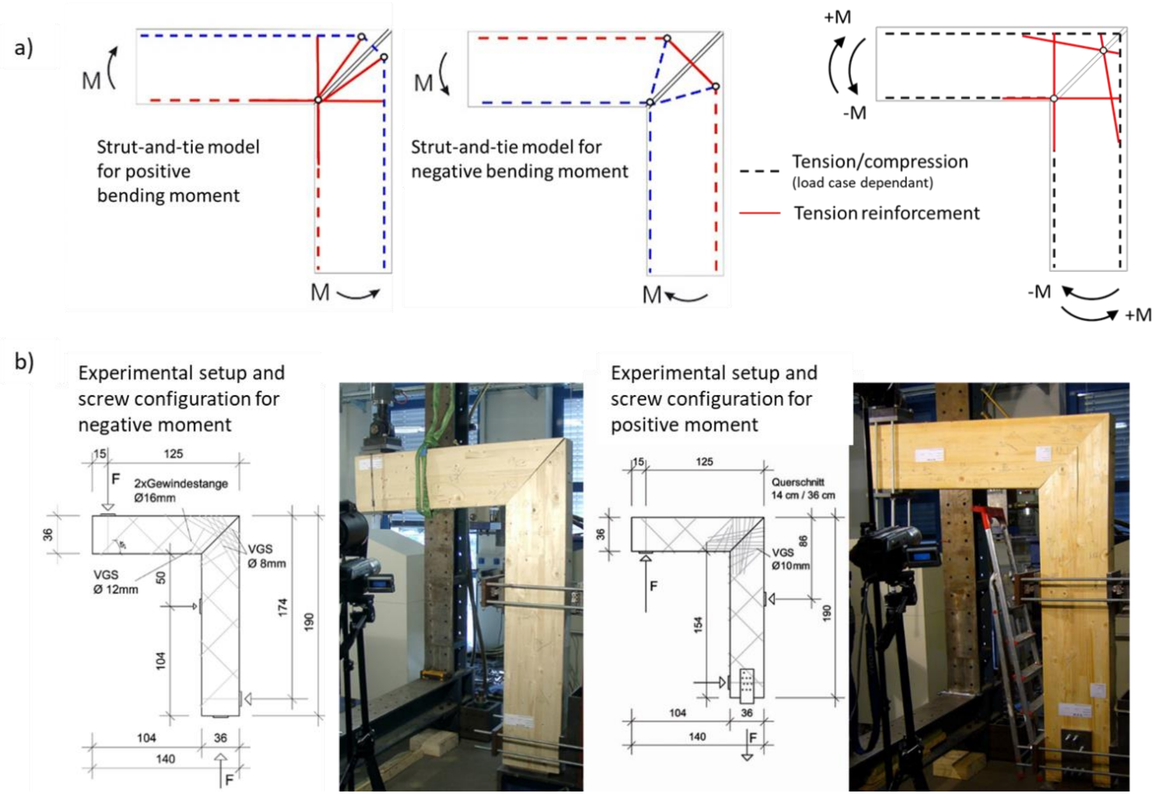

Fig.4: Rigid frame corner joint, realized with self-tapping-screws: a) simplified strut-and-tie modelling for the rigid frame corner; b) screw configurations and experimental tests of the rigid frame corners for positive and negative bending moment [7-13].

3.1. Beam- and truss-structures from glue-laminated components

Glue-laminated timber parts improved the structural applicability and potential of wood in the field of beam-, frame- and truss-structures. The systemic disadvantage of wood, the weakness lateral to grain, and the relative weakness of joints and mechanical fasteners, can be prevailed using self-tapping screws as joint elements and as reinforcement of highly stressed zones .

3.2. Reinforcing and joining timber components with self-tapping screws

Alike reinforced concrete the arrangement and the inner forces of timber reinforcement with self-tapping screws can be derived with the help of strut-and-tie models (Fig.4). Configurations of screws allow for to transfer of much more load over joints as conventional bar dowels and tin-plate joints [7-13]. Where concrete reinforcement is mainly induced to overcome tensile forces causing cracks, timber reinforcement may be introduced to influence the inner force flow of beams or other building components. The much higher performance in terms of stresses and stiffness of the steel screws compared to wood helps to overcome the poor stress performance particularly lateral to grain, also cross to the main force flow (see Fig. 5).

Fig. 5. Test specimen of reinforced timber

3.3. Raw-Timber Structures

Traditional timber production is associated with masses of wood waste that can only be partly reused for pre-products. The bulk of the wood remaining must be handled by forestry and vanish unused in nature. Naturally grown and unrefined wood may also be curved and include forks, which technically represent a very rigid joint of timber elements. To use those forks in a structural context for buildings and other structures, another way of constructing bar- and beam structures must be applied [14]. This method is the Off-Knot- Construction or Off-Knot-Design. It provides a design of bar and beam structures, where structural knots and joint are separated and connections between structural elements do not coincide with joints, but are translocated, ‘offset’ along the length of the structural elements (=> ‘Off-Knot’). Off-Knot-Construction may be applied to steel construction, where the structural knots are prefabricated and welded together or may be applied to raw timber construction with natural wood parts, given in geometry and dimensions by nature, and joined together afterwards. Whereas traditional design of bar and beam structures unifies always structural knots with joints. Joining raw timber elements, metal or hardwood interfaces may be used. Designs with naturally grown timber needs other simulation methods and other methods of stress calculation as wood is structurally used as a whole with its natural polar sections of variable local stiffness and strength [15], [16].

Fig. 6. Object examples with raw timber: chair and connection of one arm and back of the chair

Fig. 7. Parts of a Raw-Timber-Truss with Off-Knot-Joints

3.4. Mycelium Composites

Wood is a ubiquitous material in many parts of the world, and nature has developed fungus to redevelop its substances of it for reuse. Mycelium processes dead wood by penetrating it by hyphae, forming a felt-like spatial net. When inoculating mycelium spores into a wood chips or wood shavings substrate, the hyphae soak it, penetrating the substrate's single grain and binding the particles together. The mycelium composite arises from this process, a formable matrix material of chipped wood and fungi. Each mycelium species prefers coniferous wood or hardwood, on which the growth of hypha depends. Concerning mycelium composites' technical properties, combining wood particles and mycelium species is crucial [17], [18].

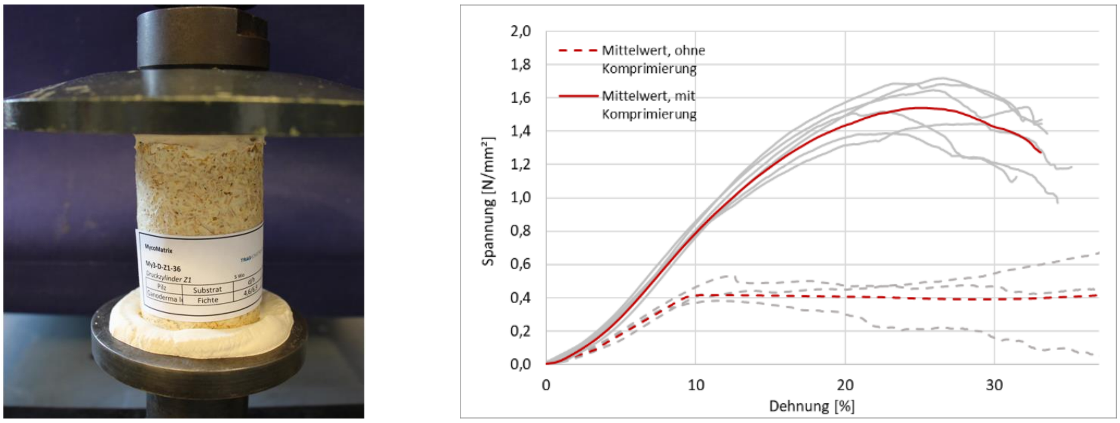

Fig. 7. Compression test of specimen of mycelium composite and load-deformation -curve.

3.4.1. Solid Building Structures

The mechanical strength of mycelium composites is moderate. It depends mainly on the substrate's wood species, the process-related treatment of the material, and the mature time provided for the transformation process. The strength of a standard mycelium composite is comparable to plastics like polyurethane (PU) or similar, which applies to lower-stress structures like solid buildings, masonry, and sandwich structures [19].

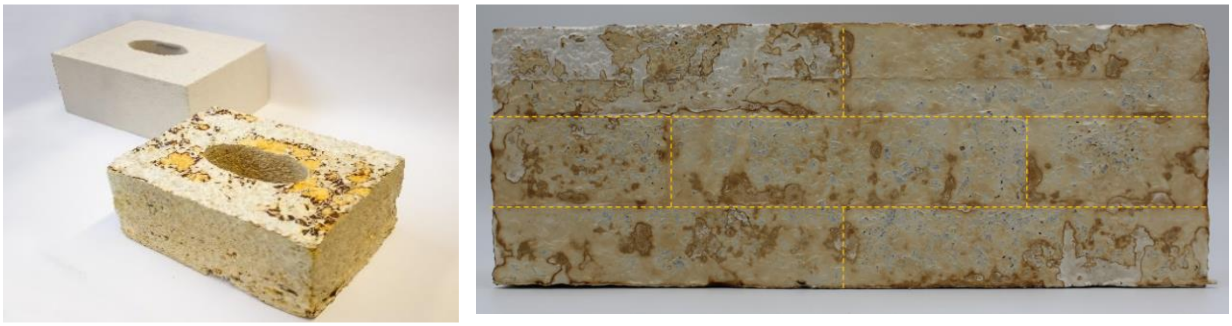

Fig. 8. Masonry-Stone and part of a brick-wall made out from mycelium composites.

- Masonry Systems

The mycelium composite is initially a living material comparable to natural materials like yeast dough, adaptable to molds to form masonry-like components. The cultivation period plays a crucial role in achieving the required strength, and it also depends on the mycelium species and the grade of transformation of the wood grain or chips. After this period, the mycelium composite will be denatured to stop the growth process and the further development of fungi. This procedure makes it possible to use the systemic advantage of living materials: as long as the bricks of a mycelium composite wall are not denatured, they keep growing and growing together, and the arising wall is – after an additional growth period - fully coherent. Mycelium composite masonry does not require additional mortar and is a homogenous natural material to be disposed of without adverse environmental consequences.

- Sandwich Structures

The binding capacity [20] of mycelium composites to wooden materials is also combined with timber boards acting as shuttering on either side and forming a Sandwich element. This may be used as wall panels or slab components within building systems, including bar and beam components, combined with self-tapping screws as the only non-biological part of this system [21].

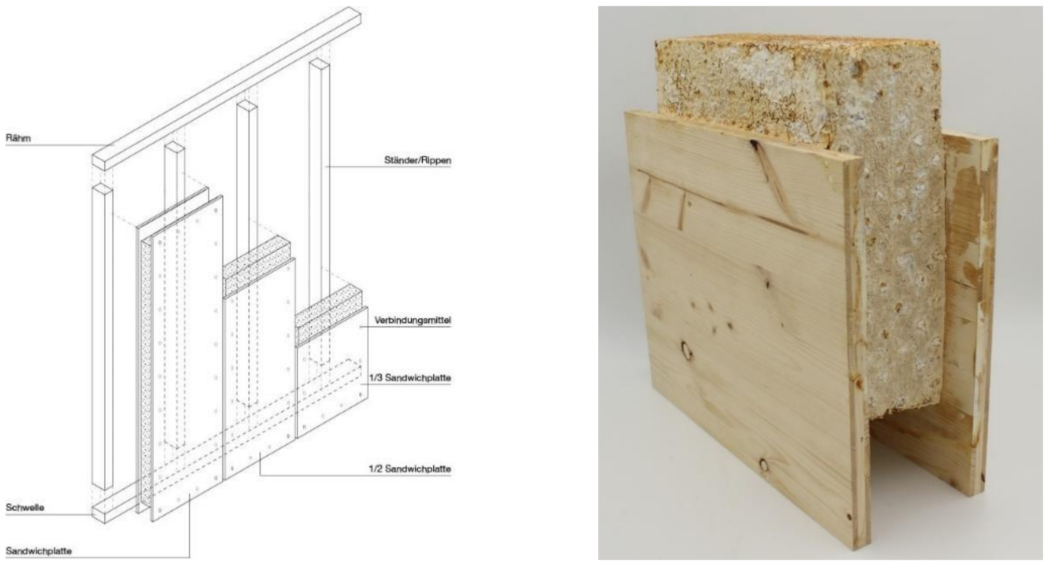

Fig.9: Sandwich – wall system with timber boards and a core of mycelium composites.

4. Resumée

Sustainable future architecture and structural engineering will not be represented only by high-tech structures and architecture with glass, steel, and plastics but also – because of a growing lack of resources – by innovative sustainable technical approaches with material saving techniques and advanced bio based materials. The progress in computer methods concerning analysis, simulation of structures, and parametric design and highly effective computer tools for scanning, processing, and archiving of 3D data as well as comprehensive biological knowledge, offers innovative methods and tools of analysis, development, and creative work. They allow innovative approaches and may be applied either to the design of material efficient and individualized structures or to develop or to brush up archaic, nature-based building techniques. It will be a matter of time until this mindset will overcome the image of fashion and become a common attitude to deal with building, structural engineering, and architecture.

References

[1] M. Trautz, T. Pohfal, and A. Seiter, "Automative body manufacturing technology for architecture", *in Detail / German Edition 7/8*, Pages/Article-Nr.:22-25, 2022
[2] T. Pofahl, G. Della Puppa, M. Trautz, D. Bailly, R. Schmit, and G. Hirt, "Self-Supporting Free-Form Structures Made of Individual Sheet Metal Panels" *in Proceedings of IASS Annual Symposia, IASS 2017 Hamburg Symposium: Advanced Manufacturing*, pp. 1-10(10), 2017
[3] G. Della Puppa, M. Trautz, "Effizienz von Faltleichtbauplatten", *in Forschungsbericht 04/2016*, Seite(n)/Artikel-Nr.: 87 Seiten, 47 Illustrationen, Shaker Verlag, ISBN: 978-3-8440-4428-7, 2016
[4] M. Trautz, T. Pofahl, A. Seiter, G. Hirt, L.-M. Reitmaier, and D. Bailly „Leichtbaukonstruktionen aus Feinblech" *in Stahlbau, 91*: Pages 375-384. https://doi.org/10.1002/stab.202200015, 2022
[5] A. Seiter, T. Pofahl, M. Trautz, L.-M. Reitmaier, D. Bailly, and G. Hirt, Gerhard, "Sheet Metal Shells", *in Baustatik Baupraxis. 23. - 24. March 2020*, Publisher: Manfred Bischoff, Malte von Scheven, Page(s)/Article-Nr.: 439-446. 2020
[6] T. Pofahl, A. Seiter, and M. Trautz, "Form finding of a sheet metal shell by generative design and pareto optimization according to the principles of structural morphology", *in Advances in Architectural Geometry (AAG)*, 04. - 07. October 2023 University of Stuttgart, 2023
[7] M. Trautz, C. Koj, „Mit Schrauben bewehrtes Holz," *in Ingenieurholzbau Karlsruher Tage 2008*; Volume: Proceedings, p. 38-45, Karlsruhe, 2008.
[8] M. Trautz,C. Koj, „Mit Schrauben Bewehren," *in Bautechnik, Bd. 85, Nr. 3*, pp. 190-196, 2008. https://doi.org/10.1002/bate.200810016
[9] M. Trautz, C. Koj, „Mit Schrauben Bewehren 2: Schubversteifung mit Schraubenfachwerken, Verstärkung von Biegeträgern mit Stahllamellen und Leistungssteigerung von biegesteifen Eckverbindungen," *in Forschungsbericht der RWTH Aachen*, Aachen, 2009.
[10] M. Trautz, C. Koj, „Self-tapping screws as reinforcement for timber structures," *in Proceedings of the International Association for Shell and Spatial Structures (IASS) Symposium 2009, Valencia*, Valencia, Spain, 2009.
[11] M. Trautz, C. Koj, „Mit Schrauben Bewehren - Neue Ergebnisse," *in Bautechnik, Bd. 86, Nr. 4*, pp. 228-238, 2009. https://doi.org/10.1002/bate.200910021
[12] M. Trautz, C. Koj, M. Ayoubi, „Fügen und Verstärken von Holzbauteilen mit Vollgewindeschrauben," *in Aachener Holzbautagung 2013*, Aachen, 2013.
[13] M. Trautz, „Vierzehn Jahre ‚Mit Schrauben Bewehren' *in: Bauforschung – Wissenschaft zur Anwendung*, S.149-164, Aachen, ISBN 978-3-95886-426-9., 2021
[14] K. Moreno Gata, A. Seiter, D. Grizmann, and M. Trautz, "Development of construction methods with naturally grown timber and bending-resistant joints", in *Proceedings of World Conference on Timber Engineering*, Oslo, Jun. 2023.
[15] K. Moreno Gata, J. Musto, and M. Trautz, "Growing Construction Components - Design and simulation strategy for self-formation following tree growth", in *Werner, L and Koering, D (eds.), Anthropologic: Architecture and Fabrication in the cognitive age - Proceedings of the 38th eCAADe Conference - Volume 2, TU Berlin, Berlin, Germany, 16-18 September 2020, pp. 51-59*, CUMINCAD, 2020.
[16] F. Spahn, K. Moreno Gata, M. Trautz, and S. Klinkel, "Image-based Modelling of Wooden Structures for Structural Computation", in *3rd ECCOMAS Thematic Conference on Computational Methods*, Dresden, Sep. 2023.
[17] Moser, F., Trautz, M., Beger, A.L., Löwer, M., Jacobs, G., Hillringhaus, F., Wormit, A., Usadel, B. and Reimer, J., 2017, September. Fungal mycelium as a building material. *In Proceedings of IASS Annual Symposia (Vol. 2017, No. 1, pp. 1-7)*. International Association for Shell and Spatial Structures (IASS).
[18] Saez, D., Grizmann, D., Trautz, M. and Werner, A., 2020, June. Analyzing a fungal mycelium and chipped wood composite for use in construction. *In Proceedings of IASS Annual Symposia (Vol. 2020, No. 5, pp. 1-11)*. International Association for Shell and Spatial Structures (IASS).
[19] M. Trautz, D. Saez, D. Grizmann, and A. Werner „Myzelkomposit als vielseitig einsetzbarer, kreislaufgerechter Werkstoff für das Bauen" *in nbau : nachhaltig bauen*, Berlin, Ernst & Sohn GmbH, p. 37-45. 2022
[20] D. Saez, D. Grizmann, M. Trautz, and A. Werner „Exploring the Binding Capacity of Mycelium and Wood-Based Composites for Use in Construction". *in Biomimetics*, 7(2), p.78. https://doi.org/10.3390/biomimetics7020078
[21] D. Saez, D. Grizmann, M. Trautz, and A. Werner, "Developing sandwich planels with a mid-layer of fungal mycelium composite for a timber panel construction system." i*n Proceedings of the World Conference on Timber Engineering,* Santiago, Chile (pp. 9-12). 2021

BIM-BASED SEISMIC RISK ASSESSMENT FRAMEWORK FOR INFRASTRUCTURE SYSTEMS

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Abstract

Building information modeling (BIM) methodology has been widely adopted for engineering projects, such as buildings, bridges, pipelines, and roads. However, BIM has yet to be fully utilized for risk assessment of critical facilities with multiple infrastructure systems. In this study, a BIM-based seismic risk assessment framework is proposed. The digital BIM model contains component-level information on the building's structural and non-structural elements, and this digital data allows the execution of component-based analysis of seismic risk. The seismic vulnerability of the components can be evaluated according to fragility curves, where each model element is attributed its corresponding fragility parameters. Each model element is assigned the median and standard deviation capacity for each damage state. Subsequently, various seismic scenarios can be simulated. The results of the simulations allow quick assessment of the seismic performance of the infrastructure and identifying the most vulnerable components. The proposed framework provides a valuable tool for engineers and decision-makers in assessing the seismic risk of infrastructures and implementing necessary measures to increase their resilience. Our preliminary work shows that BIM can provide valuable information and visualization tools for seismic risk assessment and can help improve the efficiency of the assessment process.

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Keywords: Building information modeling (BIM), Seismic risk assessment, Infrastructure, Fragility curves, Vulnerability.

1. Introduction

Over the past few decades, modern societies have become increasingly dependent on critical infrastructures (CIs) to function properly continuously, particularly during extreme and hazardous events [1], [2]. Extreme events can cause significant damage to these infrastructures, resulting in severe economic and human impacts. The impacts of seismic events on structures and infrastructure systems can be significant and widespread, affecting not only the physical structures themselves but also the surrounding environment and communities [1].

Common examples of CIs are listed in Table 1. These CIs regularly consist of several structural and non-structural components that include utilities, HVAC systems (Heating, ventilation, and air conditioning), generators, fire alarm systems, and more. Each component responds differently to a given risk scenario, rendering overall CI risk assessment a complex task. Therefore, developing efficient frameworks for CI risk assessment can be extremely valuable, as it allows better quantification of overall risk at the component-level. Visualization has been proved to of utmost importance when engineers must convey their conclusions and recommendations to decision makers in an accessible and easily understood format [3]. Powerful and advanced tools could be used to provide visualization tools to aid the decision-making process by presenting complex information. In turn, this can lead to better preparedness, thus policies and measures aimed at increasing the resiliency of communities in face of life-threatening scenarios [4], [5]

Table 1: Examples of CIs

Type of CI	Examples
Energy	Power plants, oil refineries, electrical grids
Transportation	Airports, highways, railways, bridges, tunnels
Water and sanitation	Water treatment plants, sewage systems
Communications and information	Internet networks, data centers, telecommunication
Emergency services	Hospitals, police stations, fire stations
Financial services	Banks, stock exchanges, payment systems
Government	Government buildings, military installations
Food and agriculture	Farms, food processing plants, distribution networks

Building information models (BIM) are digital representations of the physical and functional characteristics of structures that allow for the storage of information in a modular and easily maintainable way. While BIM has been initially developed for buildings, BIM has been extended to manage various types of infrastructures [6]. The architectural and engineering industry is rapidly integrating BIM for enhancing the collaboration between various engineers and stakeholders and improving the building design and construction process[7]. Numerous researchers have demonstrated how BIM can be utilized to deliver powerful visualization tools. Nevertheless, the potential of BIM is far from being realized, particularly in the context of risk assessment.

Component-level information refers to detailed data on the individual parts or components that make up a building or infrastructure system. In the context of BIM, component-level information includes characteristics such as the geometry, size, shape, materials, costs and physical properties of each component. This information is stored in a digital format, allowing for different types of analyses. This potential has been realized by different researchers. For example,[8] use a case study of a reinforced concrete (RC) frame building to demonstrate the use of BIM to select between three decision-making scenarios with different seismic retrofit strategies and alternatives. Vitiello et al. (2019) demonstrated how BIM can be employed for handling large amounts of information for the objective of cost estimation of repairs following seismic events [9]. Xu et al. (2019) developed an algorithm for damage prediction at the component-level. There, they coupled the BIM components with performance groups based on FEMA P-58. Accordingly, the costs of repairs following a seismic event can be computed and visualized [10].

In this paper, we propose a methodology for utilizing BIM so that the risk to a CI can be evaluated at the component level. We focus on the example of seismic hazard. The seismic risk assessment process involves extracting information from the properties of the BIM model components. The seismic vulnerability of the system's components is represented by fragility curves that are matched to each component's properties. Subsequently, the seismic vulnerability of each component is calculated based on the hazard curve. Finally, the vulnerability of each component is visually represented in a 3D model. We explain the key terms related to seismic risk assessment and discuss the challenges and limitations of the proposed methodology.

2. Methodology

The proposed BIM-based seismic risk assessment framework consists of five steps, as illustrated in Figure 1. These steps are hereby outlined in the Sections 2.1-2.5.

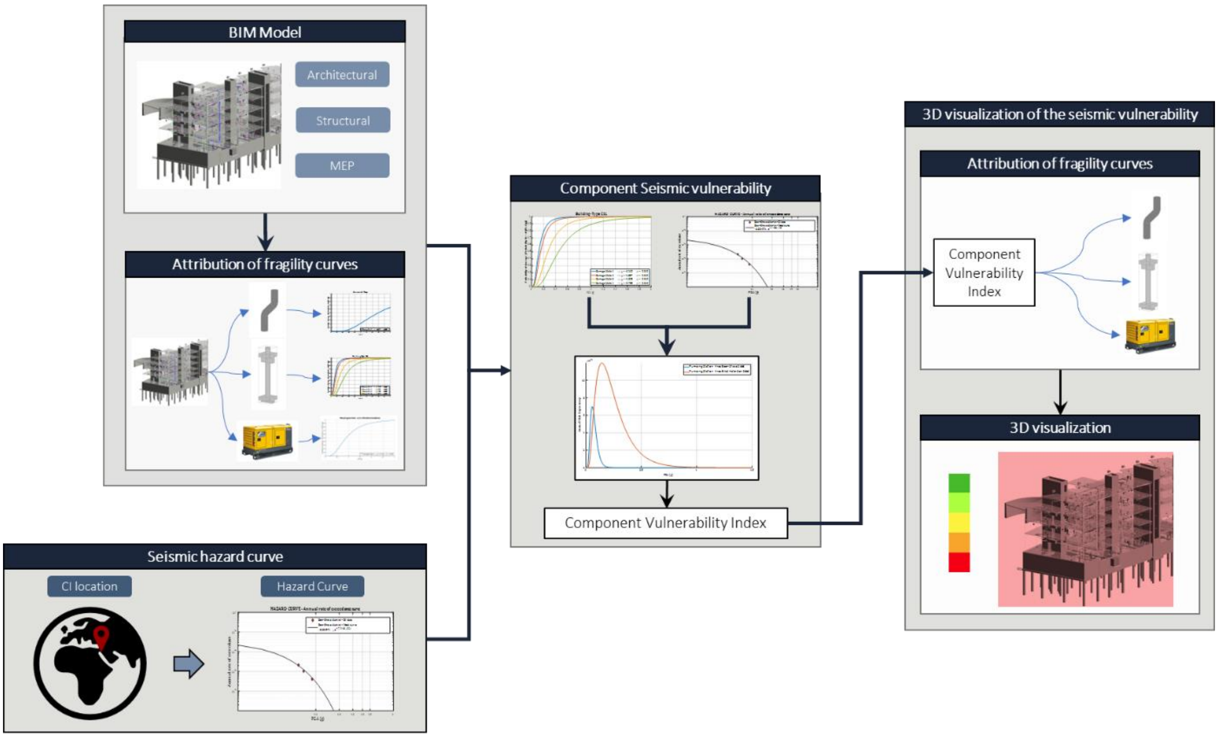

Figure 1 - Methodology framework

2.1. Structure or infrastructure system BIM model

The first step in the methodology is the creation of a digital BIM-model containing detailed information on the structural and non-structural elements of the infrastructure system. This model should include component-level geometry, material properties, and connection details. For the example in the current paper, the model is created and managed in Autodesk Revit software. This model serves as the foundation for subsequent steps in the seismic risk assessment process. It is crucial to define the necessary level of information within the model to ensure accurate and reliable assessments.

2.2. Attribution of fragility curves to each model element.

The second step involves attributing fragility curves to each component in the BIM model. A fragility curve is a graphical method to express the probability of a component or system exceeding a certain damage state (DS) as a result of an earthquake's intensity measure (IM) parameter. As shown in Figure 2, fragility curves for a structure, system, or components are represented as a lognormal cumulative distribution function (CDF), which requires two parameters to be fully defined: the median capacity of the component to resist damage state (θ_{ds}) and the standard deviation of the capacity (β_{ds}). In the case of multiple and sequential damage states, the damage states are ordered by damage severity (from least severe to the most severe damage), and the fragility function defines the probability of being in a specified damage state (Eq. 1).

$$P(DS = ds_i|IM) = \begin{cases} 1 - P(DS \geq ds_i|IM) & i = 0 \\ P(DS \geq ds_i|IM) - P(DS \geq ds_{i+1}|IM) & 1 \leq i \leq n-1 \\ P(DS \geq ds_i|IM) & i = n \end{cases} \quad (1)$$

DS	Uncertain damage state of a particular component $\{0,1,\ldots N_n\}$
ds	A particular value of DS
N_{DS}	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 a damage state ds measured in terms of IM
β_{ds}	The logarithmic standard deviation of the uncertain capacity of the component to resist a damage state ds

The fragility curves are generated based on empirical data, analytical studies, or expert judgment [11].The data of fragility parameters for structure and system infrastructure, and for individual components can be found in the literature [12]–[15]. In this research, we use this data to assign fragility parameters to the BIM-model components. Each component in the BIM model is attributed with fragility parameters: the median and standard deviation capacity for each damage state. This step may require integration with external databases or tools for the generation and assignment of fragility curves.

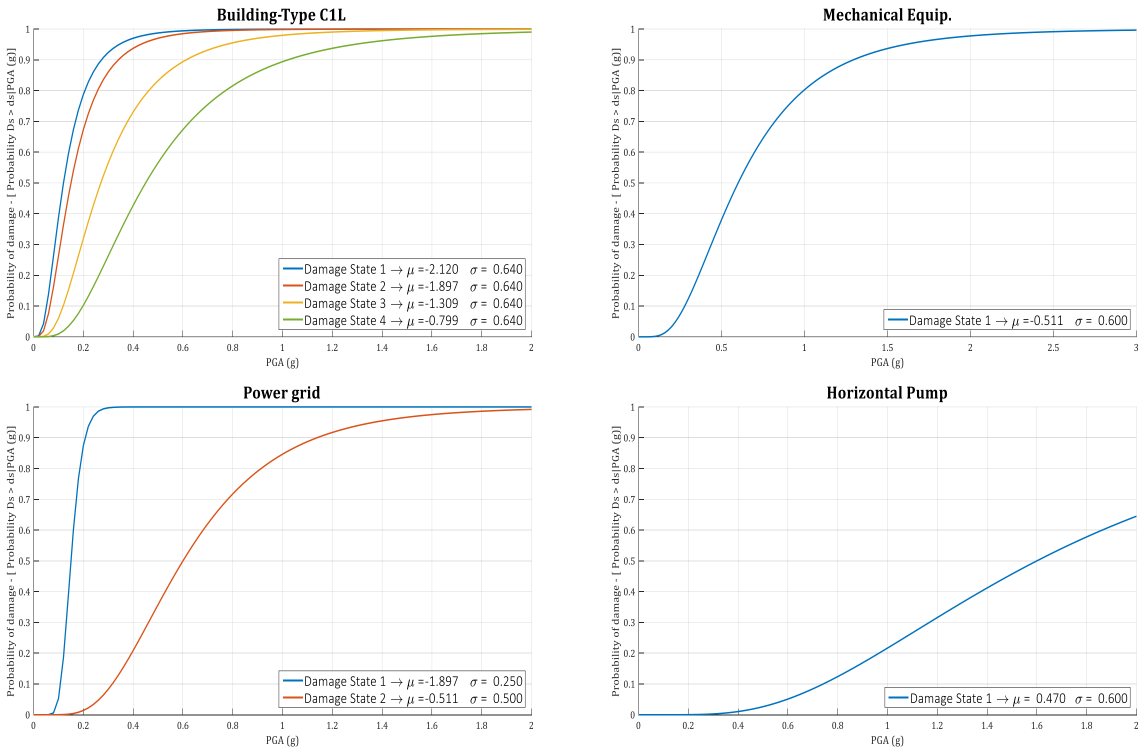

Figure 2 - Example of fragility curves for different types of possible infrastructure components

2.3. Derivation of a seismic hazard curve

The seismic hazard curve is derived for the infrastructure system's location, taking into account the seismicity of the region, local soil conditions, and other relevant factors. The hazard curve represents the relationship between the probability of exceedance of a given ground motion level and the corresponding return period. This curve is essential for determining the seismic demand on the infrastructure system and is typically obtained from regional seismic hazard studies or through probabilistic seismic hazard analysis (PSHA).

2.4. Calculation of the seismic vulnerability

In this step, the seismic vulnerability of each component is calculated by combining the fragility curves and the seismic hazard curve. For each component, the probability of exceeding each damage state is evaluated under various seismic scenarios. This involves calculating the conditional probability of exceeding a specific damage state given a certain ground motion level and then integrating over the range of possible ground motion levels. The result is a vulnerability index for each component, which quantifies the likelihood of the component experiencing different levels of damage under seismic loading.

2.5. 3D visualization of the seismic vulnerability

The final step in the proposed methodology is the 3D visualization of the infrastructure system's seismic vulnerability. The BIM environment allows for an interactive exploration of the vulnerable components and damage states. This visualization enables engineers and decision-makers to quickly identify the most vulnerable components and assess the overall seismic performance of the infrastructure system. Furthermore, the visualization can be used for communication with stakeholders and to support decision-making processes related to seismic retrofitting, maintenance planning, and emergency response.

By integrating the detailed component-level information available in BIM models with the seismic risk assessment process, the proposed framework offers a comprehensive and efficient approach for evaluating the seismic vulnerability of infrastructure systems. This approach can support the development of targeted strategies for enhancing the resilience of these systems in the face of seismic hazards.

3. Case Study: Seismic Risk Assessment of a Sewage Pumping Station

To demonstrate the effectiveness and feasibility of the proposed BIM-based seismic risk assessment framework, a conceptual case of a sewage pumping station is discussed. The pumping station is a critical component of a wastewater management system. Its primary function is transporting sewage or wastewater from lower-elevation areas to higher-elevation areas, enabling the wastewater to continue to a treatment facility through gravity-fed sewer systems or pressurized pipes. In order to ensure continuous operation of the system during and after a seismic event, it is crucial to assess the pumping station's seismic vulnerability and implement necessary measures.

The sewage pumping station considered in this case study is a reinforced concrete structure located in a seismically active region. The pumping station has two pumps, electrical systems, pipes and valves, and other non-structural components necessary for its operation. A BIM model of the pumping station was created using Autodesk Revit, including general information on the structural and non-structural elements.

The analysis follows the five steps of the proposed BIM-based seismic risk assessment framework:

- Creation of a BIM model: A detailed digital BIM model of the sewage pumping station was created, including information on the structural and non-structural elements.
- Attribution of fragility curves to each model element: Fragility curves were attributed to each component in the BIM model based on the median and standard deviation capacity for each damage state obtained from the literature.
- Derivation of a seismic hazard curve: A seismic hazard curve was derived for the location of the pumping station. The hazard curve considers regional seismicity, local soil conditions, and other relevant factors.

- Calculation of the seismic vulnerability of each element: The seismic vulnerability of each component was calculated by combining the fragility curves for each damage state and the seismic hazard curve.
- 3D visualization of the element's seismic vulnerability: The seismic vulnerability of the pumping station and its components was visualized in a 3D model. The visualization presents the vulnerability based on the classification of each color.

The results of the case study highlight the effectiveness of the proposed BIM-based seismic risk assessment framework in identifying the most vulnerable components of the sewage pumping station. The 3D visualization will enable to quickly assess the overall seismic performance of the infrastructure system and prioritize potential retrofitting and maintenance efforts.

4. Discussion and Conclusion

The BIM-based seismic risk assessment framework presented in this paper represents a step forward in the application of BIM for infrastructure seismic risk assessment. By leveraging the detailed component-level information available in BIM models and attribution with fragility curves and hazard analysis, the proposed framework provides a comprehensive and efficient approach for evaluating the seismic vulnerability of infrastructure systems at component level. This approach can support the development of strategies for enhancing the resilience of these systems in the face of seismic hazards.

The use of BIM for seismic risk assessment offers several advantages. First, the component-level information available in BIM models can improve the accuracy the risk assessment process. By attributing fragility parameters to individual components, it is possible to account for variations of different components properties that may impact the seismic performance of the infrastructure system. This concept can be especially valuable for identifying vulnerable components and prioritizing retrofitting and maintenance efforts. Second, by incorporating seismic risk assessment into the BIM environment, it becomes possible to track and manage the vulnerability of the infrastructure system over time and to update the risk assessment as new information becomes available. Finally, the 3D visualization capabilities of the BIM environment offer powerful tools for communicating the results of the seismic risk assessment to stakeholders and decision-makers. It becomes easier to convey complex information and support decision-making processes related to seismic retrofitting, maintenance planning, and emergency response.

In conclusion, this paper has presented a framework for BIM-based seismic risk assessment for infrastructure systems. The proposed framework combines the component-level digital information available in BIM models with fragility curves and hazard analysis to provide a comprehensive and efficient approach for evaluating the seismic vulnerability of infrastructure systems. The study has demonstrated the potential of BIM to improve the accuracy and efficiency of the seismic risk assessment process and to support the development of targeted strategies for enhancing the resilience of infrastructure systems in the face of seismic hazards.

As the adoption of BIM in the engineering and construction industry continues to grow, there are significant opportunities to further refine and expand the application of BIM for infrastructure risk assessment. Currently, work is underway to refine the code and to allow to explore the integration of other types of hazards and risk assessment methodologies into the BIM environment, as well as the development of advanced tools for visualizing and managing risk information throughout the infrastructure lifecycle.

5. Limitations and further research

The proposed methodology still requires additional work that includes coding and verification of results. Furthermore, the work is limited to simple single-story facilities, as more complex solutions are required to cope with structures with multiple floors. In such cases, it would be required to perform a structural analysis to identify the intensity on each floor and only then calculate the risk. A further constraint is that the methodology requires prior knowledge of the fragility parameters for each structural component. If there is no prior knowledge of the fragility parameters, they need to be assessed.

While we have focused on seismic hazard, it is possible to use the proposed methodology to assess other types of risks. However, this requires modifying the methodology according to the unique characteristics of each risk.

References

[1] A. Urlainis, D. Ornai, R. Levy, O. Vilnay, and I. M. Shohet, "Loss and damage assessment in critical infrastructures due to extreme events," *Saf Sci*, vol. 147, p. 105587, Mar. 2022, doi: 10.1016/J.SSCI.2021.105587.
[2] A. Urlainis, I. M. Shohet, R. Levy, D. Ornai, and O. Vilnay, "Damage in critical infrastructures due to natural and man-made extreme events - A critical review," *Procedia Eng*, vol. 85, pp. 529–535, 2014, doi: 10.1016/j.proeng.2014.10.580.
[3] T. Munzner, *Visualization Analysis & Design*. 2014. doi: 10.1201/b17511.
[4] FEMA, "Seismic Performance Assessment of Buildings - FEMA P-58," 2012.
[5] A. Urlainis and I. M. Shohet, "Seismic Risk Mitigation and Management for Critical Infrastructures Using an RMIR Indicator," *Buildings*, vol. 12, no. 10, Oct. 2022, doi: 10.3390/buildings12101748.
[6] A. Mitelman and U. Gurevich, "Implementing bim for conventional tunnels - A proposed methodology and case study," *Journal of Information Technology in Construction*, vol. 26, 2021, doi: 10.36680/j.itcon.2021.034.
[7] R. Sacks, C. Eastman, G. Lee, and P. Teicholz, *BIM Handbook*. 2018. doi: 10.1002/9781119287568.
[8] N. Caterino, I. Nuzzo, A. Ianniello, G. Varchetta, and E. Cosenza, "A BIM-based decision-making framework for optimal seismic retrofit of existing buildings," *Eng Struct*, vol. 242, 2021, doi: 10.1016/j.engstruct.2021.112544.
[9] U. Vitiello, V. Ciotta, A. Salzano, D. Asprone, G. Manfredi, and E. Cosenza, "BIM-based approach for the cost-optimization of seismic retrofit strategies on existing buildings," *Autom Constr*, vol. 98, 2019, doi: 10.1016/j.autcon.2018.10.023.
[10] Z. Xu, H. Zhang, X. Lu, Y. Xu, Z. Zhang, and Y. Li, "A prediction method of building seismic loss based on BIM and FEMA P-58," *Autom Constr*, vol. 102, pp. 245–257, Jun. 2019, doi: 10.1016/J.AUTCON.2019.02.017.
[11] A. Urlainis and I. M. Shohet, "Development of exclusive seismic fragility curves for critical infrastructure: an oil pumping station case study," *Buildings* , vol. 12, no. 842, Jun. 2022, doi: 10.3390/buildings12060842.
[12] P. Gehl, N. Desramaut, A. Réveillère, and H. Modaressi, "Fragility Functions of Gas and Oil Networks," *Geotechnical, Geological and Earthquake Engineering*. 2014. doi: 10.1007/978-94-007-7872-6_7.
[13] Alliance American Lifelines (ALA), "Seismic Fragility Formulations For Water Systems," 2001.
[14] NIBS, "HAZUS-MH: users's manual and technical manuals. Report prepared for the Federal Emergency Management Agency. National Institute of Building Sciences," 2004.
[15] T. Rossetto, D. D'Ayala, I. Ioannou, and A. Meslem, "Evaluation of Existing Fragility Curves," *Geotechnical, Geological and Earthquake Engineering*, 2014, doi: 10.1007/978-94-007-7872-6_3.

AUXILIARY EQUIPMENT FOR WORKING AT HEIGHTS: WORKERS' PERCEPTION OF SAFETY ISSUES

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Abstract

Falls from height are a relevant occupational health and safety problem, given the significant impact they have on an injured worker, as well as on their families and the company to which they belong. Although most countries are trying to reduce the number of accidents due to this cause, the injuries resulting from these accidents are usually severe. The causes of falls from height are varied, including lack of control by the direct supervisor, irresponsibility of the worker or wrong handling. Also, they can be caused by auxiliary elements (platforms, ladders, machinery or others) required for the execution of a task, which needs to be assembled appropriately or safely. This article provides the context of using auxiliary equipment (fixed and mobile scaffolding and safety rail) for work at height. Then, a field information survey is carried out to describe the main problems regarding their use on-site. Finally, through the application of 44 semi-structured interviews with construction professionals and supplier companies in the Chilean market, different appraisals on the safety of working at heights and the use of auxiliary equipment are described. The results show that the relevant aspects in the use of auxiliary elements to prevent the risk of falls are related to the singularity of the projects under construction, the scarcity of regulations or their updates, in addition to the lack of technical information on-site that would allow the constant verification of auxiliary equipment, among others.

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Keywords: falls, safety, safety rail, scaffolding, work at height

1. Introduction

The increase in building demand implies increased work performed on platforms or scaffolding. Work performed at a height greater than 1.8 meters from the ground is considered risky [1] and is one of the leading causes of severe accidents and mortality. For example, in 2013, in the United States, it represented mortality of 36.9% [2], while in China, from 2012 to 2016, approximately 2,850 construction employees lost their lives due to on-site accidents, with an average number of 1.57 deaths per day, where falls represent 55% of fatal accidents [3]. In Chile, in 2021, falls from different levels accounted for 26.8% of deaths due to occupational accidents [4]. Working at height is a very relevant issue for the country since, due to the scarcity of building land, the solution to housing needs has been densification through high-rise construction. This challenge requires more significant analysis, control, monitoring and recommendations for using these systems in high-rise construction projects [5].

Regulatory standards are one way to ensure that platforms and guardrails are assembled and manufactured under general conditions, are structurally responsive and meet minimum safety requirements. A study in Japan on the effectiveness of a regulatory framework on reported accidents in the construction sector showed that, within one year of implementation of regulations for platforms at height, accidents decreased by 33% [6]. Another study in Spain showed that having certified platforms for work at height through an established regulatory framework increases the safety level from 4.36 to 5 [7]. Another study conducted in the United States [8] concluded that after five years of enacting of the OSHA (Occupational Safety and Health Administration) revision of 1996, the accident rate decreased by 20%. In addition, Cheung & Chan [9] recommend some essential measures to prevent severe injuries and fatal falls while working from scaffolds, such as inspecting all its components. Specifically, they mention the importance of supervision by competent personnel for scaffolds to be erected, moved, dismantled or altered, as well as strictly complying on-site with the scaffold manufacturers' guidance regarding these activities. For their part, Błazik-Borowa & Szer [10] specify as important the design of the scaffolding installation but indicate that, due to difficulty or absence of regulations, this phase requires time that is not necessarily available on-site. The same with the costs involved in preparing site-specific designs, so contractors forego creating the design and run the risk of assembling the scaffolding without any design.

Concerning to the use of guardrails, studies in Japan and New Zealand raise the relevance of regulation to standardize these systems and recognize the importance of using temporary edge protection to reduce the risk of falling. However, in the case of New Zealand, previous evaluations on recommendations of structural aspects still need to be completed [11]. On the other hand, the study by Çelik et al.[12] conducted in Turkey and Iran discusses the importance of guardrails having homogeneous and transparent criteria that mainly indicate the procedures for installation, assembly and disassembly, and inspection to be carried out by competent professionals, as well as guidelines for manufacturers and suppliers. In Brazil, Filho and Serra [13] compared two types of collective protection, in which, besides verifying the performance of each of them in the field, they evidenced the lack of technical information for the execution of guardrails. Penaloza et al. [14], comparing nine types of edge protection systems, show the importance of not only evaluating structural aspects of the systems but also other criteria such as safety, efficiency (in assembly and disassembly) and product flexibility (for the use of different types of projects) to choose between one or the other in an informed manner.

Since scaffolding and guardrails are temporary constructions on a construction site, they are considered of minor importance. Therefore, no relevance is given to the process of their assembly/disassembly and use, causing severe or fatal accidents. Therefore, this study seeks to describe the safety assessment in using these systems to help decision-makers evaluate specific criteria or support the implementation of new or improved regulations.

2. Methodology

The methodology used corresponds to a mixed approach, combining three data sources. First, a review of different aspects of fall hazards related to using platforms and guardrails conducted based on a bibliographic review that included national and international regulations, and existing studies on the subject. Secondly, a field information survey was carried out by observing different high-rise building projects in the Metropolitan Region (Chile) and visualizing the use and problems detected using these systems. Thirdly, a qualitative study consisted of 44 semi-structured interviews with construction professionals and suppliers in the Chilean market. The interviews sought to understand how these auxiliary systems are used in work at heights, their problems and needs regarding their use and the technical aspects that need to be reviewed.

3. Results

Four topics regroup the main results: description of fall risks in the construction sector, description of safety problems detected on-site, regulatory analysis of the use of work platforms and guardrails, and appraisals on safety in using platforms and guardrails.

3.1. Fall hazards

Slip, trip and fall incidents, mainly fall from height, are a leading cause of injury in the New Zealand residential construction industry [15]. The most common origins of falls from height in this sector are ladders, scaffolding and roofs [16]. Furthermore, accidents involving temporary access systems (mainly temporary scaffolding) account for many worldwide injuries in the construction industry [17]. A study in Malaysia [18] conducted during the period 1997- 2000 indicates that scaffolding accidents are due to construction errors, lack of protective equipment, inadequate foundations, poor technical condition and excessive load on the scaffold.

A similar situation is evident in Chile. According to data from the Asociación Chilena de Seguridad, 95% of the causes of falls are due to human cause, due to erroneous personal actions, among which the following stand out: lack of workers' knowledge regarding the risks or procedures for working at heights, as well as lack of technical skills for handling platforms (the worker only knows his job and not the functioning or operation of the equipment) or physical (dizziness, balance problems or altered health factors) [19]. The other 5% corresponds to environmental factors related to the auxiliary elements to perform work at height, such as non-existent or inadequate standards, or normal wear of the auxiliary elements; problems of design, manufacturing or defective installation of the elements or parts that make up the platforms to work at height [20]. Although using auxiliary elements only represents 5% of the causes of the problem, it becomes a critical aspect to study. Falls from different levels can cause consequences to workers' health that can often be serious and even fatal. This situation is relevant because, there are gaps in Chilean regulations related to scaffolding structures and guardrails, which expose workers to severe accidents due to falls from heights.

3.2. Safety issues on-site

Field observation of the use of scaffolding and guardrails showed that three major safety problems cause falls: human factors, environmental factors and technical aspects. Regarding human factors, the worker performs improper actions such as: (1) loosening or not using the lifelines, (2) not using all the safety elements or misusing them, (3) climbing the scaffolding structure or leaning on the railings, (4) not respecting the instructions of direct supervisors or risk prevention specialist, (5) not analyzing or observing the conditions of the task and possible risks, and (6) lacking or non-using work procedures. The environmental aspects are mainly related to the climatic conditions of the place where the work is performed, such as gusts of wind that cause the platform to sway, rain that makes the platform slippery, or glare from the sun, which interferes with the tasks. Concerning the technical aspects, there was a lack or absence of elements, such as (1) perimeter railings or structure fastening elements (Fig 1b), (2) accessories that ensure the balance, position and fixation of the structure or that ensure the vertical movement of the structure or brake, (3) scaffolding in poor condition, with wear and tear or structures that are not calculated (or poorly calculated), unstable, overloaded, with missing fastenings or incomplete (Fig. 1a), (4) incorrect assembly or insufficient working platforms.

a b

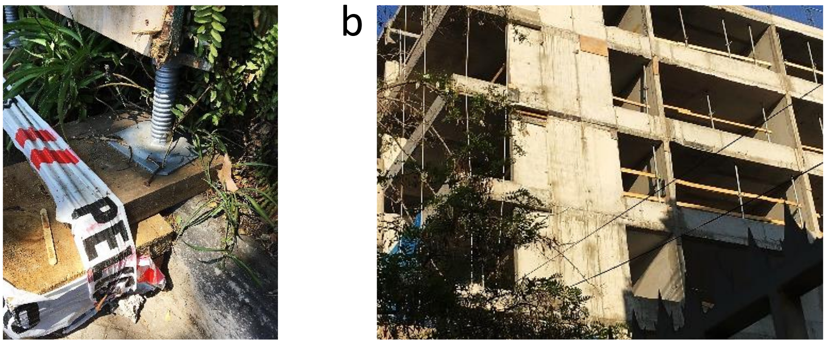

Fig. 1. (a) first picture; (b) second picture. (CCC-caption style)

3.3. Regulatory analysis

Concerning to the analysis of international regulations, these include several documents that detail the use of scaffolding and prevention measures to avoid accidents when working at height. Also, it contains the steps for the correct assembly and disassembly of the equipment and, depending on the country, includes specific criteria for the design, type of structures and requirements for which the manufacturer is responsible. In Latin America, the level of regulations is low. In Colombia, responsibility is delegated to the manufacturer through a certification system, where platforms must also comply with resolutions updated every year [21]. Some articles on mobile scaffolds exist in Argentina, Paraguay and Ecuador. However, these are incomplete or specified only for suspended scaffolds and do not apply to mechanically elevated platforms [22]. In Peru, Bolivia and Chile, there are regulations only for fixed scaffolds [23]. On the other hand, when comparing international regulations with Chilean regulations, it is observed that in Chile, there is a gap in terms of more detailed information on the structure and materiality of the equipment, prevention and safety measures for working at heights, and documents for checking or periodically inspecting scaffolding and guardrails indicating their condition.

3.4. Safety considerations

Semi-structured interviews were conducted with construction project workers, professionals and suppliers of national products, seeking a varied sample regarding the relationship between scaffolding and guardrails (direct operators, supervisors, managers, suppliers). A total of 44 interviews were conducted, audio-recorded and transcribed for a thematic content analysis that allowed grouping the experience of the participants in seven main sections presented: inspection, modifications, training, maintenance, security plans, normative, and product standardization.

3.4.1 Inspection

Three entities can carry out this task for inspecting these auxiliary systems: a public agency, a technical inspector who depends on the client, and a risk prevention specialist who works for the construction company. Regarding the inspections carried out by the public agency, these inspections need to be increased. On some occasions, the technical knowledge of those who carry them out need to be improved, and that there is no standard procedure to ensure that the inspection is the same for all the works and equipment. Regarding the technical inspector's supervision, several suppliers pointed out that their review is stricter abroad than in Chile since they are mainly involved in administrative tasks in Chilean projects. Regarding the work of the risk prevention specialist, he is in charge of checking that the system is installed correctly and, in several projects, he marks with coloured cards whether the system can be used. That is to say, and he gives the "green light" for its use. Unfortunately, due to cost issues, the number of risk prevention specialists must be increased for large-scale projects.

3.4.2 Modifications

Significant modifications to the platforms are related to incorporating of fabrics that cover the scaffolding, generating a sail effect, or the hanging of advertising, generating stresses that were not considered in the design. It is important that when a modification must be made, the scaffolding is closed using safety cards. Regarding the reasons for the changes, it is mainly mentioned that the solutions must be adapted/modified due to project conditions (project progress or areas with complex geometry). As project plans are usually modified several times before and during the project’s progress, the supplier companies cannot provide a quality service when they offer an edge protection system. Several times the leasing of the product does not correspond to the total perimeter of the project or with the best structural characteristics for the singular or blind points. On the side of the construction companies, as the progress of the project must be fast, they point out that the supplying companies delay the delivery of the offer and choose not to lease elements for the total perimeter that should have a protection system, using different types of protection that do not perfectly cover the perimeter.

3.4.3 Training

The mobile scaffolds delivered by the suppliers to the worksites do not include the work of operators. These personnel are dedicated to training the worksite workers who will use the scaffolds. Thus, it is mentioned that the most common accidents are linked to the danger of falls from heights and entrapment with the lifting mechanisms. In general, training is provided by the supplier, so it is important to be clear about who must attend these training, according to the responsibilities they will have in the process. Regarding the technical competencies that installers of these systems must have, they must have previous experience. In addition, when using scaffolding, workers must have specific knowledge of the model. They must also have physical conditions suitable for working at heights.

3.4.4 Maintenance

In Chile, there is no traceability procedure after the sale of guardrails or scaffolding; therefore maintenance level after the product is still being determined. Most interviewees agreed to perform preventive maintenance on the scaffolding and guardrails and the parts that may be subject more significant wear and tear, providing evidence of their performance.

3.4.5 Security plans

The primary safety shortcomings detected by the interviewees associated with the use of scaffolding were using it without being certified, not assembling it according to the plan, not respecting the information on the cards, and misuse of personal protection elements, such as the use of helmets without chinstraps or the misuse of safety harnesses. Among the problems encountered in the assembly/use/disassembly/maintenance of scaffolding, the following are mentioned: lack of scaffolding parts, misinterpretation of the plan, poor site planning and problems with cleaning associated with inadequate scaffolding maintenance. On the other hand, in the case of a critical structure, a design and a report are requested from the company that supplied the scaffolding or guardrail with its respective engineering support. Among the control points, it was found to verify that the area where the scaffolding or guardrail is to be placed is unobstructed, that it is assembled according to the supplier's instructions, and verify that the scaffolding and guardrail have all their parts and that they were correctly placed.

3.4.6 Normative

Finally, regarding scaffolding standards, it was mentioned that when scaffolding and guardrails are purchased abroad, they come with international standards and that national standards are old and should be updated or do not exist. Most of the products used in Chile are imported, so they should be certified when they arrive in the country or at least obtain a homologation in certified laboratories. However, as the homologation process can be expensive, the option of carrying out field tests should also exist. Regarding whether there are relevant elements related to the design, assembly, use and disassembly of scaffolding that should be considered in a standard but still need to be included, it was pointed out that there is a gap in safety issues rather than manufacturing or structure standardization issues. The need to go deeper into the capabilities of the personnel that assemble the equipment and into safety measures more aligned with the equipment currently in Chile was raised. It is also mentioned to consider the seismic analysis of temporary structures, since it is a different approach at the time of design, and to include more in-depth classification by materiality in the designation of scaffolding.

3.4.7 Product standardization

Regarding products, the characteristics that construction companies prioritize, in addition to cost, are the weight of the system (for easy installation or relocation), ease of modularization and configuration, additional options for unique joints (for example, in curved areas) or special projects, and the person-hours required to make changes or relocations. They also identify the need for improvements in fastener types, which could be more standard or encompass systems that do not require a specif width or spacing. In addition, they mention the support of engineers and architects to harmonize structural and architectural characteristics that allow for repetitive use of the protection system.

4. Conclusion

The article addressed the issue of falls from height in the construction industry and the importance of using auxiliary equipment, such as scaffolding and safety railings, to prevent such accidents. The study added a survey of field information in the Chilean market through 44 semi-structured interviews with construction professionals and supplier companies to describe the main problems regarding using auxiliary equipment on site. The study identified inspection, modifications, training, maintenance, security plans, regulations, and product standardization as the seven main sections of the study. The findings indicate that the significant modifications to the scaffolding are related to incorporating fabrics that cover the scaffolding or hang advertising, showing efforts not considered in the design. The supplier provides the training, and it is important to know who should attend the training according to their responsibilities in the process. Safety issues are related to using scaffolding without certification or not erecting it according to plan. The study highlights the need to increase inspections, improve the technical knowledge of inspectors and the importance of maintenance and safety to prevent falls from height.

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References

[1] M. Tonetto and T. Saurin, T. A. “Choosing fall protection systems in construction sites: Coping with complex rather than complicated systems”. Safety Science, 143,. 2021, doi: 10.1016/J.SSCI.2021.105412
[2] E. Nadhim, C. Hon, B. Xia, I. Stewart and D.Fang. “Falls from Height in the Construction Industry: A Critical Review of the Scientific Literature”. International Journal of Environmental Research and Public Health, 13(7). 2016, doi: 10.3390/IJERPH13070638
[3] B. Shao, Z., Hu and autres six autors. “Fatal accident patterns of building construction activities in China”, Safety Science, 111, 253-263, 2019, doi: 10.1016/j.ssci.2018.07.019
[4] Superintendencia de Seguridad Social. “Estadísticas de accidentabilidad 2021 - Chile”. Presentación. 62pp. 2022
[5] M. Meza, E. Bedoya and C. Severiche-Sierra. “Aspectos técnicos de seguridad en barandas para el riesgo de caídas”, Journal of Industrial Neo-Technologies, 5(1), 22-29, 2018.
[6] K. Ohdo, Y. Hino and H. Takahashi. “Research on fall prevention and protection from heights in Japan”. Industrial Health, 52(5), 399–406. 2014, doi: 10.2486/INDHEALTH.2014-0137
[7] J. Rubio-Romero, M. Rubio and C. García-Hernández. “Analysis of construction equipment safety in temporary work at height”. Journal of Construction Engineering and Management, 139(1), 9-14. 2013, doi: 10.1061/(ASCE)CO.1943-7862.0000567
[8] A. Yassin and J. Martonik. “The effectiveness of the revised scaffold safety standard in the construction industry”. Safety Science, 42(10), 921–931. 2004, doi: 10.1016/J.SSCI.2004.05.001
[9] E. Cheung and A. Chan. “Rapid demountable platform (RDP)—A device for preventing fall from height accidents”. Accident Analysis & Prevention, 48, 235-245, 2012, doi: 10.1016/j.aap.2011.05.037,
[10] E. Błazik-Borowa and J. Szer. “The analysis of the stages of scaffolding “life” with regard to the decrease in the hazard at building works”. Archives of Civil and Mechanical Engineering, 15(2), 516–524. 2015, doi: 10.1016/J.ACME.2014.09.009
[11] A. Escamilla, M. García and N. Pérez. “Static load behavior and energy absorption of safety guardrails for construction works”. Revista de la Construcción, 15(2), 46-54, 2016, doi: 10.4067/S0718-915X2016000200005
[12] G. Çelik, S. Aydinli and S. Bazaati. “Safety net applications in developing countries: Turkey and Iran case study”. Journal of Construction Engineering, Management & Innovation, 4(1), 12-21, 2021, doi: 10.31462/jcemi.2021.01012021,
[13] M. Filho and S. Serra. “Comparison between collective protective systems in Brazil: safety platforms and safety net type V”, Applied Sciences, 2, 1-12, 2020, doi: 10.1007/s42452-020-03838-0,
[14] G. Penaloza, T. Saurin and C. Formoso. “Identification and assessment of requirements of temporary edge protection systems for buildings”. International Journal of Industrial Ergonomics, 58, 1-19, 2017, doi: 10.1016/j.ergon.2017.02.005,
[15] H. Hsiao. “Fall prevention research and practice: a total worker safety approach”. Industrial health, 52(5), 381-392. 2014, doi: 10.2486/indhealth.2014-0110
[16] S. Rokooei, B. Javan and A. Nazari.” Effects of Virtual Reality Safety Training on Critical Construction Accidents”. Proceedings of the Creative Construction e-Conference, 2022, doi: 10.3311/CCC2022-036 279-287
[17] S. Whitaker, R. Graves, M. James and P. McCann. “Safety with access scaffolds: Development of a prototype decision aid based on accident analysis”. Journal of Safety Research, 34(3), 249-261, 2003, doi: 10.1016/s0022-4375(03)00025-2
[18] N. Hamdan and H. Awang. “Safety scaffolding in the construction site”. Jurnal Teknologi, 75(5). 2015
[19] Corporación de Desarrollo Tecnológico.“Normas y elementos de protección - Seguridad en Altura”. Revista BiT N°92, 26–29. 2013
[20] A. Zermane, M.Tohir, M. Baharudin and H. Yusoff. “Risk assessment of fatal accidents due to work at heights activities using fault tree analysis: Case study in Malaysia”, Safety Science, 151, 1-12, 2022, doi: 10.1016/j.ssci.2022.105724,
[21] D. Díez Castro and L. Quintero Corzo. “Estudio de factibilidad económica y técnica para la introducción de andamios prefabricados en aluminio en el mercado colombiano” (Bachelor's thesis, Universidad de La Sabana). 2012
[22] L. Calles. “Proyecto de prevención de riesgos profesionales en obras de construcción enfocada en andamios”. Tesis de Grado. Unidad Académica de Ciencias de la Ingeniería y Aplicadas. UTC. Argentina 77 p. 2009
[23] S. Pérez-Albela Rodríguez. “Análisis comparativo técnico – económico de plataformas elevadoras y andamios colgantes en trabajos de acabados en fachadas”. Tesis de Grado. Pontificia Universidad Católica del Perú, Perú. 2020

STUDY ON THE RELATIONSHIP BETWEEN SUSTAINABLE CITIES AND URBAN ENGINEERING MANAGEMENT IN UNDEVELOPED COUNTRIES - A CASE STUDY OF TIMOR-LESTE

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Abstract

Timor-Leste is an emerging country, and its capital city, Dili, has excellent potential to become a paradigm for a sustainable city in the future. However, the procedure still needs to overcome many difficulties and challenges. Firstly, in this paper, literature collecting and expert interview methods are used to summarize the urban development experiences of Timor-Leste and Taiwan based on their geographical similarities. Secondly, the relationships between future urban engineering management in Timor-Leste and sustainable cities are established. The findings of this study not only underscore the criticality of effective urban engineering management in fostering sustainable urban development but also furnish pivotal insights that can inform the trajectory of sustainable urban and urban engineering management in Timor-Leste. The present study's outcomes hold the potential as a point of reference for pertinent international research endeavors.

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Keywords: Timor-Leste, Taiwan, sustainable city, urban development, urban engineering management

1. Introduction

Urbanization has led to a growing demand for urban engineering. Timor-Leste can learn from other countries with similar conditions for sustainable development. Sustainable urban development is crucial for economic growth and quality of life. Taiwan's approach emphasizes innovation, collaboration, and policy frameworks. This article summarizes Taiwan's experiences and explores potential directions for Timor-Leste. It may serve as a reference for future research to enhance urban development efforts.

This paper employed literature review and expert interview as research methods. The literature collection utilized online search engines and AI tools to gather relevant keywords related to the research topic, while the expert interview was conducted by a research team of four professionals with expertise in engineering management, land use, urban planning, and language translation. The collected literature was categorized into four main parts: urban development in Timor-Leste, urban development in Taiwan, urban disasters, engineering management, and sustainable cities. The research team analysed and organized the documents separately and explored vital factors and their correlations between engineering management and sustainable cities in Timor-Leste through expert interviews. The results were subsequently summarized in this paper.

2. Overview of East Timor

Timor-Leste, a new country located between Indonesia and Australia, currently has limited income and a little diversified economy focusing on agriculture. However, there are significant opportunities and potential for economic growth. The government aims for a modern, diversified economy with high-quality infrastructure and a shift towards commercial and small-scale agriculture. The country faces challenges with floods and erosion, particularly in urban areas like the capital city of Dili, but the government is implementing appropriate programs to manage these issues. Access to safe water supply and electricity is also a pressing issue, with the government implementing a rural electrification program to connect remote areas to the national grid and reduce poverty levels. [1]

3. City development of Taiwan

In Liu and Tung's (2003) study, it was observed that Taiwan experienced a rapid increase in urban population from 33% to 78% between 1956 and 2000 [2], surpassing the growth rate of the United States. The urban planning system in Taiwan, influenced by American pragmatism, prioritizes rapid and concentrated economic activity and population growth but needs more flexibility to address the diverse needs of modern cities. Consequently, the development of Taiwan's urban planning has undergone several stages, but current challenges, such as extreme climate risks, social polarization, and improving quality of life, require adaptation.

Taiwan's early agricultural, rural period (1600-1894) saw the emergence of rural patterns that varied based on topography and water resources, resulting in compact settlements, linear settlements, and scattered settlements. Agricultural towns by streets gradually developed to facilitate trade between villages. Two major economic centers emerged in the north and south of Taiwan, with the urban population accounting for about 8% of the total population of Taiwan.

During the Japanese occupation (1895-1945), major public works projects, including transportation development, greatly impacted urban and town development. Taipei City experienced a rapid increase in population, with regional and local centers developing along longitudinal railways and highways approximately 50-80 kilometers apart. The government emphasized the development of modern agriculture, water conservancy, public health, and primary education, leading to increased agricultural productivity and surplus production to support urban development.

The middle period of urban development (1950-1980) saw the establishment of labour-intensive industries in the 1950s, planning industrial areas in and around cities to address the rural population surplus. Urbanization and suburbanization occurred from 1950 to 1970, with increased public investment in infrastructure from 1973 to 1978. However, illegal farmland factories emerged due to rising legal land prices in urban industrial areas, leading to traffic congestion, environmental pollution, and soaring land prices. The problem of illegal farmland factories remains unsolved in Taiwan.

The urban development of Taiwan during 1990-2010 saw the establishment of science parks of industrial (SPI) to upgrade industries and expand exports, with the first SPI established in 1980. The construction of urban public facilities prioritized advanced transportation systems that emphasized energy conservation and carbon reduction. However, this further accentuated urban primacy in Taipei.

In Taiwan's post-urbanization era, there is increasing concern regarding the impact of urban disasters and the necessity to prioritize the quality of urban public infrastructure, risk management, and urban renewal. The earthquake in central Taiwan in 1999, Typhoon Morakot in central, southern, and south-eastern Taiwan in 2009, and the petrochemical gas explosions in Kaohsiung City in 2014 have emphasized the need to address aging infrastructure, poorly constructed public buildings, enhance risk management, and raise public awareness.

In recent years, the Taiwan government has improved accessibility in central and southern Taiwan by strengthening transportation infrastructure and developing industrial parks, facilitating the balanced movement of industries and population, and reducing the gap between urban and rural-urban development. [3] Additionally, in response to the United Nations' sustainable development goals, the Taiwan government has actively expanded green investment, promoted sustainable urban development, implemented housing justice, improved the urban environment and transportation construction, and enhanced people's quality of life.

Furthermore, as Taiwan is one of the countries most impacted by complex natural disasters globally, the government is considering climate change in decision-making. It is committed to building a green economy while changing resource use, carbon emissions, and environmental damage in the economic growth process to reduce the impact of extreme weather events on Taiwan's urban and financial sectors. [4]

4. Modern sustainable city

4.1. Humanistic design

Urban development has been shaped by various movements and challenges throughout history. The United Nations World Health Organization emphasizes the importance of human-centered design principles for urban living environments. Human factors play a critical role in urban development, and successful practices are based on environmental awareness and local democracy. Effective environmental governance requires a political process, from small-scale community efforts to national policies.

4.2. Construction energy consumption and engineering quality

Construction energy consumption is a significant global issue that requires detailed assessment and investigation. Professional Construction Management (PCM) can improve construction project performance and quality while reducing costs. Intelligent buildings, green buildings, and ecological engineering are essential in sustainable development, and elements such as actual energy use and building materials are closely related to achieving sustainable objectives. Unmanned Aerial Vehicle (UAV), Building Information Modeling (BIM), Building Energy Modeling (BEM), and the Internet of Things (IoT) are key information technology (IT) factors to improve engineering quality [5]. Combining these technologies enables intelligent urban engineering, creating sustainable and nature-integrated cities [6].

4.3. Sustainable urban development

In the 1970s, Florida enacted the Growth Management Act to guide local land use patterns. Sustainable urban management prioritizes "software" aspects such as laws, finance, and education, and values openness, continuous improvement, participation, and innovation. Sustainable action involves setting indicators and charters, managing environmental accounting, leading public sector initiatives, and using economic, social, and administrative mechanisms to promote environmental improvement. The United Nations' 2030 Sustainable Development Goals include SDG 6 on clean water and sanitation, SDG 9 on industry, innovation, and infrastructure, SDG 11 on sustainable cities and communities, and SDG 15 on land life relevant to the development of sustainable cities. Focusing on these goals from the beginning can help developing countries like Timor-Leste avoid the challenges faced by already-developed countries.

4.4 Urban Building Management

In Timor-Leste, adherence to local customs and traditions is important for modern buildings, and sustainable development is necessary for urban design and construction to showcase the unique design culture. Rapid construction without proper planning and engineering quality management can cause significant social, environmental, and economic problems. Encouraging residents' participation in urban construction through interdisciplinary dialogue is key to unique contemporary architectural development.

Improvement in the hardware aspect of urban development is necessary and should be integrated into urban ecological management. Cohen (2018) emphasizes that people are the most critical factor in improving the quality of life [7]. Therefore, ecological communities and cities must cultivate residents' ecological habits and culture. Based on Taiwan's urban development experience, the following recommendations are advanced:

- Public and private buildings: Improve structural durability, energy efficiency, water conservation, and greenery, incentivized through rewards or subsidies based on environmental resources, indicators, ecological examinations, and design standards.
- Public domain: Construct public domains, open spaces, residential communities, and urban ecological networks that reserve green spaces, use the permeable pavement, enhance ecological functions and network of open spaces, construct comfortable pedestrian and bicycle systems, and have traffic optimization designs for residential communities and essential activity nodes.
- Public infrastructure: Improve the engineering quality of public infrastructure, including planning, design, construction, and management and maintenance, based on safety, economy, convenience, and comfort principles in regular and disaster times. Ecological indicators and medium- to long-term spatial enhancement plans should also guide hardware improvements.

5. Conclusion

Sustainable urban development is crucial for urban public works and housing construction in Timor-Leste. Local experiences and global dialogues are necessary for promoting sustainable development, with economic strategies such as the result of transportation networks and urban settlements being essential. Legal regulation and education are crucial tools for governance, and environmental taxation can effectively change behaviors, leading to energy and resource conservation and pollution reduction. To showcase the unique design culture of Timor-Leste, sustainable development is necessary, and local customs and traditions should be considered. Improving the hardware aspects of urban development requires medium-to-long-term spatial enhancement plans, and ecological habits and culture need to be cultivated among residents. The management of urban engineering quality is emphasized as a crucial factor in sustainable urban development, and several future challenges for sustainable urban development in Timor-Leste are proposed in this paper and findings serve as a basis for future research on urban development issues in Timor-Leste and as a reference for relevant international research.

Reference

[1] Timor-Leste strategic development plan 2011 – 2030, Timor-Leste government(2010) Available: https://wedocs.unep.org/handle/20.500.11822/9800;jsessionid=82F79694EC530C0B530559FF1F07B1F8
[2] Liu, Paul K. C., An-Chi Tung(2003),” Urban Development in Taiwan: Retrospect and Prospect,” Journal of Demography, No. 26, pp.1-25. (in Chinese). Available: http://www.psc.ntu.edu.tw/jps/pub/26/assets/1.pdf
[3] National Development Plan (2021-2024), Taiwan government(2021), National Development Council, ROC (Taiwan). Available: https://www.ndc.gov.tw/Content_List.aspx?n=D61190201622DA50&upn=5E8A39A0E8888B41

[4] 2020 Annual Report NSD, Taiwan government(2020), National Council for sustainable development, ROC (Taiwan). Available: https://ncsd.ndc.gov.tw/Fore/nsdn/implement2/annualReport
[5] Chen, Yih-Tzoo, Tseng-Huang Chung(2022)," Using Cloud Technology for Construction Mobile Device Inspection and Big Data Statistics," Journal of the Chinese Institute of Civil and Hydraulic Engineering, Vol. 34, No. 6, pp. 579–588 (in Chinese) , doi: 10.6652/JoCICHE.202210_34(6).0003
[6] Chen, Shih-Ming(2020), Strategy of Applying BIM Combined with AI/IoT/GIS/Big Data to The Full Life Cycle of Building Construction Project, Ministry of the Interior, Taiwan. (in Chinese), Architecture and Building Research Institute, Ministry of the Interior, ROC (Taiwan). Available: https://www.abri.gov.tw/News_Content_Table.aspx?n=807&s=214330
[7] Cohen, T.(2018), The sustainable city, Columbia University Press, New York, USA.

PROMOTING SUSTAINABLE CONSTRUCTION WASTE MANAGEMENT OF BUILDING PROJECTS IN OMAN

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Abstract

As the globe faces environmental difficulties, sustainable construction techniques have become of importance in recent years. Construction waste management is a significant area of concern since improper management may have a large negative impact on the environment. To reduce the negative effects on the environment and guarantee the effective use of resources, Oman has to encourage sustainable construction waste management techniques in construction projects. Tons of rubbish are produced by Oman's building sector, which has grown rapidly over the past 20 years, placing a strain on the country's present waste dumping facilities. Random construction trash disposal is a persistent problem that is linked to the Sultanate's governorates accelerated urban expansion. Unplanned disposal of Contractors' primary activities results in construction waste in public spaces, wadis, residential areas, and agricultural land, all of which have major negative effects. Due to this move, the municipality's legality division made the decision to amend some regulations and create new ones to curtail this phenomenon and safeguard the ecology and environment from improper garbage disposal. Be'ah Company in the Sultanate of Oman also intends to use building debris to build roads all throughout Oman. To lessen the impact of this material on the disposal sites, construction waste management (CWM) is crucial. The main goals of the research are to evaluate the environmental and social effects of reducing and recycling the demolition and construction waste of building projects, as well as to analyze the status and trends of building construction waste generation in Oman. They also include evaluating the cost-effectiveness of the approaches used to manage construction waste in Oman. To achieve these goals, a variety of methods are used. For example, a questionnaire is distributed to various participants in various industries, interviews have been conducted with various individuals holding higher positions in various businesses and ministries, such as the Be'ah Company and the Muscat Municipality, and finally, previous related research articles are reviewed. The results of this study aids in the creation of policies and strategies for encouraging environmentally friendly methods of disposing of building debris in Oman. Additionally, it offers suggestions for stakeholders in the construction sector on how to enhance trash disposal procedures and lessen the environmental effect of construction projects nationwide.

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Keywords: sustainability, waste management, construction industry, construction waste

1. Introduction

The construction industry is a major contributor to waste generation worldwide. In Oman, the construction sector is rapidly developing, resulting in a significant increase in waste generation. The improper management of construction waste can lead to environmental pollution, health hazards, and economic losses. Therefore, it is essential to promote sustainable construction waste management practices in Oman.

With more focus on the environmental effects of numerous industries, including building, sustainable development has recently become a crucial worldwide problem. Waste produced by the construction industry contributes to resource depletion, pollution, and environmental deterioration. Promoting sustainable building waste management has emerged as a critical necessity for nations all over the world, particularly Oman, to solve these issues. Government of Oman is focusing on implementing new and effective techniques to manage its construction waste. Be'ah company has 21 landfill sites spread throughout several governorates in Oman. Barka and Musanah operated sites by Be’ah received, from 2015 to 2017, an estimated 4,668,044 tons of garbage. In 2018, North Al Batinah Site and Raysut also began to be operated by the same company. Additionally, in 2019, Be'ah began operations Rustaq site, South Al Sharqiya, Dakhliyah, Buraimi, Ibri, and AL Amerat, receiving a total of 3,955,904.56 tons of C&D waste.

To keep up with the increased demand for infrastructure and real estate, Oman, a nation that is undergoing fast urbanization and economic expansion, has seen a boom in construction projects. Significant environmental and social issues are presented by the possibility for increased waste creation and poor waste management practices that come with this expansion. To maintain sustainable development in Oman's building sector, it is essential to establish efficient waste management policies and systems.

This study aims to identify problems and offer remedies for encouraging sustainable construction waste management in Oman building projects. This study aims to add to the body of knowledge on sustainable building practices in the Omani setting by examining the present waste management procedures, identifying important issues, and assessing possible possibilities. Policymakers, building industry experts, and other stakeholders will benefit greatly from the research's conclusions, which will help them make wise decisions and put sustainable waste management strategies into practice. This study aimed to accomplish many significant goals by encouraging sustainable methods of managing building trash. First off, it will lessen resource depletion, pollution, and greenhouse gas emissions associated with construction-related activities. Second, it will promote circular economy concepts, lessen the need for landfilling, and help with resource efficiency. Additionally, it will encourage the development of a safer and better working environment for construction employees, improving their productivity and general well-being.

A comprehensive strategy will be used in the research, combining qualitative and quantitative techniques. Data will be gathered through surveys, site visits, and interviews to provide a comprehensive picture of Oman's construction waste management methods and difficulties. To find transferrable ideas and solutions that may be modified for the Omani context, the research will also explore pertinent literature, laws, and best practices from other nations. Overall, by offering doable suggestions for enhancing Oman's construction waste management methods, this research aimed to close the gap between theory and reality. The construction industry in Oman can make major strides toward becoming a more socially and ecologically responsible sector by working together and implementing sustainable solutions, which will help the nation realize its larger aim of sustainable development.

2. Research Significant

The research is exploring the current state of construction waste management practices in Oman and identify ways to promote sustainable construction waste management in building projects. This research may contribute to the development of policies and strategies for promoting sustainable construction waste management practices in Oman. Additionally, the research is providing recommendations for construction industry stakeholders to improve waste management practices and reduce the environmental impact of building projects in the country. Construction waste causes resource depletion, pollution, and greenhouse gas emissions, all of which contribute to environmental deterioration. The aim of the research is to reduce the detrimental environmental effects by considering sustainable waste management techniques for the construction industry. Effective waste management practices can help Oman in conserving its ecosystems. It minimizes pollution, preserve natural resources, and reduce resource depletion.

The construction sector may help with resource conservation, recycling, and the development of a closed-loop system by using sustainable waste management techniques. By reducing the use of virgin materials and landfilling, this strategy will encourage a more robust and sustainable building industry in Oman. Sustainable waste management techniques can also have a positive financial impact. Construction organizations may reduce material costs, streamline project timeframes, and improve overall project efficiency by using tactics including waste reduction, reuse, and recycling. The construction sector in Oman will gain knowledge from this research about cost-effective waste management techniques that can enhance resource allocation and lower operating costs. Overall, this research is crucial in promoting sustainable development in Oman and ensuring that the construction industry adopts environmentally responsible practices for the benefit of the country's future generations.

3. Literature Review

One of the biggest global producers of solid waste is the construction sector. Massive volumes of construction waste have been produced by constructing new buildings, remodeling, and demolition projects. Managing construction waste ensures a healthy and sustainable built environment. Sultanate of Oman began its Renaissance in 1970. Since that date, every industrial sector has growth steadily. The construction industry has emerged as a key sector among these industries, and it has made significant improvements in recent years. Yearly, there are tons of waste generated by construction industry in Oman.

Literatures reviewed and identified the key themes, concepts, and best practices related to sustainable construction waste management practices. It emphasizes the significance of waste management and sustainable construction methods in achieving environmental and social sustainability objectives [1]–[5]. The effects of building waste on resource depletion, pollution, and climate change are discussed, placing emphasis on the necessity of efficient waste management techniques. Previous studies evaluate the sources of construction and demolition waste as well as the variables affecting waste generation rates. Identifying various waste categories, such as inert and non-inert compounds, as well as their quantities in the waste stream are part of these studies.

Various waste management approaches and tactics, such as waste reduction, reuse, recycling, and suitable disposal procedures, are explored in the literature. It presents examples of effective waste management techniques used worldwide and explores the advantages and difficulties related to each strategy. Construction waste management is considered in relation to the circular economy idea. The establishment of closed-loop systems, resource conservation, material recovery, and other circular economy tenets are all covered in the literature. It looks at how these ideas might be used to manage waste from building projects while encouraging resource efficiency and reducing trash production.

Many literatures [6]–[9] discussed deeply the state of knowledge on sustainable construction waste management. It serves as the foundation for identifying gaps in the body of knowledge and aids in providing recommendations and policies for encouraging environmentally friendly waste disposal methods in the context of construction projects in Oman. In addition, the responsibilities of the different project stakeholders have been discussed and analyzed. On the other hand, it showed the importance of the collaboration between various stakeholders in implementing and considering the concept of sustainable construction waste management during the whole project life cycle.

4. Construction Material Waste Generation Factors

Sand, bricks, concrete, plastics, glass, wood, and other materials are all included in construction and demolition waste. However, it's crucial to remember that demolition and building debris contains more than 50% of items that landfills cannot take. Therefore, these materials must be separated from the rest of the construction and demolition waste before being disposed of in landfills. Clean concrete and asphalt, for example, may be sorted properly so that they can be recycled and applied to new building projects.

Depending on the project's location, scale, and its construction activities, different construction operations generate waste in different ways. Construction waste is mostly generated during handling of materials, procuring, and construction activities along with the residual wastes on site. The general flow of the materials required for building on site is depicted in Figure 1.

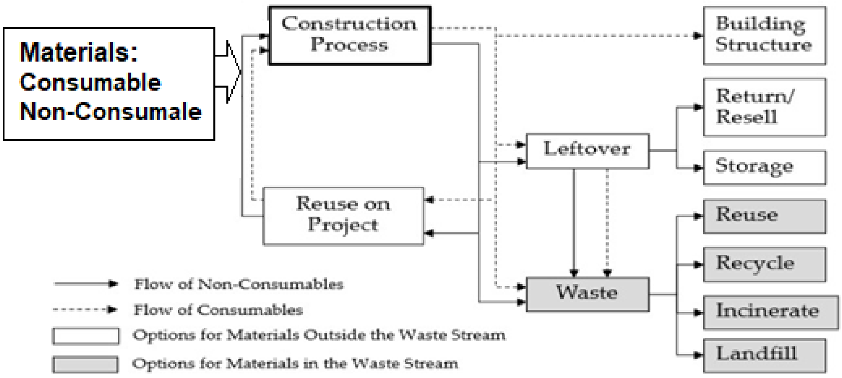

Figure 1: Cconstruction materials flow pattern adopted from Gavilan & Bernold (1994)

According to (Bekr (2014), the significant sources of construction waste materials include incomplete designs, design errors, poor documentation, rework due to poor quality, storage shortages, improper materials storage, poor waste management strategies, unfavorable site conditions, a lack of skilled labor, incorrect quantity estimations, materials damaged during transportation, theft, and vandalism. Up to nine categories have been utilized in previous research and literature to group these aspects, including building process, design, procurement, used equipment, used materials, labor and human behavior, project, owner, and weather. These aspects were further divided into four sections by Luangcharoenrat et al. (2019): materials and procurement, building technique and planning, design and documentation, and human resources. It is clear that effective waste management is essential in construction, and categorizing the sources of waste can help improve waste management practices. Sustainable waste management practices are necessary for sustainable development, which aims to meet the needs of the present without compromising the ability of future generations to meet their requirements. Four categories—design and documentation, materials and procurement, construction method and planning, and human resources—comprise a total of 28 causes of construction waste [12]. These elements include subpar design, excessive material ordering, a lack of stakeholder communication, inadequate staff training, and more.

5. Construction waste minimization concept

One of the most significant environmental issues worldwide is the management of construction and demolition waste. Large quantities of waste are generated from ongoing new construction works, renovation, and demolition work. Waste management comprises several activities, including waste gathering, transportation, storage, treatment, recovery, and disposal. On-site sorting of construction and demolition waste is a reliable and efficient technique for waste management.

Reducing waste in construction projects leads to various benefits. Generally, it improves the competitiveness of local contractors by minimizing/decreasing construction costs and increasing visibility for the company. In addition, minimizing waste has ecological benefits by reducing the amount of waste sent to landfills and extending its lifespan, as well as improving resource utilization and efficiency. Finally, waste minimization can positively impact the quality of construction materials and reduce the environmental impacts of construction, such as reducing the depletion of natural resources. By managing and minimizing waste on projects, it is possible to make more effective use of construction materials and reduce the significant amount of construction waste. This can contribute to tangible improvements in the quality of construction materials without raising costs resulting from incompetent design and the quantity of materials sent to the landfill during the construction phases via efficient waste management [6], [13].

The key drivers of construction waste management are sustainable, economic, and environmental aspects. Economics appears to be the most significant factor for key players such as clients or contractors, as their main aim is to maximize their profits. As a result, the main driver of waste management is economic motivation. Environmental considerations drive governments and their requirements to consider health and environmental factors in managing the construction waste process. Over the years, the concept of sustainability has become a concern for governments, the public, and industries. As a result, it is necessary to ensure that all activities are carried out with relevant sustainable concepts. According to [14], the drive to reduce and minimize waste can be divided into three main categories: legislative, economic, and environmental. Legislative drivers include government decrees and laws, policies for organizations, and contractual terms and conditions. Economic drivers involve considering the recycling of generated waste. The third driver, environmental, involves sustainability rating systems that aim to control resources and material handling by providing guidance that may reduce environmental threats.

Omer et al., (2022) confirmed that implementing efficient recycling solutions for building debris can offer a number of advantages for the environment and for businesses. It could benefit the environment by lowering the volume of waste dumped in landfills, preserving natural resources, and lowering greenhouse gas emissions. Businesses may see cost savings as a result of decreased disposal costs and higher sales of recycled materials. Additionally, implementing sustainable practices can improve a business's brand and draw in clients who care about the environment. Newaz et al., (2022) outlined various difficulties with CD&W administration. The primary barrier to efficient waste management was noted to be the absence of uniform state legislation.

6. Research methodology

The research study objectives are achieved using a mixed-methods technique. The research starts with a deep evaluation of the literature on international application of sustainable building waste management strategies. A survey of Oman's construction industry stakeholders was then conducted to evaluate the condition of the sector's waste management procedures and determine the obstacles it faces in implementing sustainable practices. In-depth interviews with significant players in the construction industry will also be undertaken in addition to the survey to better understand the issues and possible solutions for encouraging sustainable waste management practices in construction projects. To identify and assess trends, patterns, and themes, the data from the literature review, survey, and interviews have been collected and evaluated using both quantitative and qualitative techniques. A mixed-methods approach was used as the technique for this study, providing for a more thorough knowledge of the condition of Oman's present sustainable construction waste management procedures. It will be feasible to uncover both the industry's difficulties and prospective solutions that may be customized for Oman by combining quantitative and qualitative methodologies.

To evaluate theoretical goals and validate hypotheses, the quantitative technique entails gathering numerical and statistical data for analysis, such as the opinions of a group of persons associated to the subject field. This approach is particularly successful in giving insights into a particular subject because it is based on the gathering of data that can later be evaluated and presented in statistical and graphical formats. The focus of the qualitative method is on linguistic terms, and it entails gathering information by asking open-ended questions such why, what, where, and how. However, because it is dependent on personal judgment, experience, and knowledge, the facts gathered might differ significantly. Additionally, qualitative data may be sharply focused on the research field to comprehend human attitudes and behavior because it is based on knowledge, experience, and personal viewpoints. Interviews, focus groups, and open-ended answer surveys are often used techniques for gathering qualitative data. To gather facts and proof, qualitative data may be evaluated using a variety of procedures, including data grouping, and sorting as well as combining concepts and patterns.

A questionnaire is designed and used to collect the required data along with interviews. The proposed questionnaire focuses on measuring specific parameters related to the research objectives. The questionnaire consists of five sections. Section one is designed to collect general information of the participants and general data related to C&D waste management. The second section is designed to measure the recommendation of the procedure to minimize the social and environmental impact of the C&D waste. In addition, it evaluates the benefits and challenges of recycling, reducing, and reusing of

C&D waste activities. The next sections are measuring the impact factors of C&D waste management on social and environment. In addition, it evaluates the sources of construction waste and actions that can be taken to minimize the C&D waste in Omani construction industry. The proposed sample size of this study is 98 with 65 responses as it's designed based on the Confidence Level, Confidence Interval, and Population Size with 95% of confidence level, and 5% of margin error. Table 1 shows the survey responses based on the participants' experiences.

Table 1 Survey respondents

Experience	Gender		Total
	Male	Female	
0-5 Years	11	7	18
5-10 Years	15	8	23
10-15 Years	12	1	13
15-20 Years	6	0	6
More than 20 Years	4	1	5
Total	48	17	65

7. Results and key findings

More than 80% of the involved participants in the study are agreed and strongly agreed with the statement of the minimizing C&D waste must be adopted in entire project life cycle starting from initiation stage till the completion and demolition as per the used Likert scale. 70.8% agreed that there is a financial benefit to the project stakeholders by selling construction waste. Regarding the plans that can be adopted to enhance the C&D waste management in Oman, 64.6% agreed with setting rules and penalties to achieve the target level. Whereas 33% agreed with offering rewards and conducting awareness sessions to enhance the management process. Also, almost all participants recommended that Oman Government should promote and support the development of C&D waste 3Rs (Reduce, Reuse, Recycle) principles. Table 2 shows the benefits that can be generated from the recommended improvements to the management of C&D waste techniques. As shown, most of the participants agreed with that reducing the demand for waste landfills, saving natural resources, achievement of green constructions, and the improvement of the AEC companies competitiveness are the major benefits from adopting the 3Rs strategy for managing C&D waste.

Table 2: Benefits of C&D waste recycling, reduce and reuse management process.

Benefits	Strongly Agreed/Agreed (%)	Neutral (%)	Disagree (%)
Save space from waste landfills, reducing the demand of new waste landfills	81.6	7.7	10.8
Saving natural resources	84.6	13.8	1.5
Reduce budget for the project by used recycled resources	47.7	40	12.3
Saving transport costs between site and waste landfill sites and save disposal costs	56.9	30.8	12.3
Compliance with government policies for green construction and conservation of the environment	90.7	9.2	0
Improving the competitiveness of AEC companies and increasing their business opportunities	92.3	6.2	1.5
Motivating the entrepreneurship in the recycling and reuse of building waste	86.2	12.3	1.5

Regarding the challenges and difficulties of considering the C&D waste recycling, reduce and reuse strategy, the major challenges are lake of standards/ awareness/governmental support, funding, poor experience, and high cost. Referring to the factors affecting on environment and social, the agreed high ranked factors are degradation of the environment should be more compensated, institutions should have environmental impact assessment system of construction waste and institutions should consider the adverse impacts of construction activities on the environment. Also, job creation, risk/accidents reduction, increasing public awareness, sustainability achievements, and effecting community monitoring and feedback are considered as the factors that have great social impact factors for considering C&D waste management strategies. The survey results showed that poor waste management, poor coordination, careless attitudes of the workers, labour behaviour, change in design, poor control/supervision, tools/equipment misuse, improper storage, are material transporting problems are the major generation factors that increases the C&D waste. Finally, the driving factors to minimize the C&D waste are effective governmental supervision, on-time environmental related institutions intervention, increase waste minimization approaches awareness to all construction stakeholders, and focusing on the benefits of reducing the demand for landfill spaces.

8. Conclusions

Promoting environmentally friendly construction waste management in Oman's construction projects may have several positive effects on the country's economy, society, and overall environment. We can reduce the damaging effects of building waste and aid in the general growth of the nation by using sustainable methods. Based on the research results, the key benefits are:

- Limiting the use of natural resources, lower greenhouse gas emissions, and decrease the amount of waste that ends up in landfills by reducing, reusing, and recycling building construction waste.
- Sustainable methods of managing waste in the construction sector could assist contractors save a lot of money. Reusing and recycling resources enables companies to minimize the demand on acquiring new materials, which in turn reduces project costs.
- The development of new recycling facilities and waste management facilities may result from the promotion of sustainable construction waste management, generating new job prospects in the industry.
- Adopting sustainable construction waste management techniques can assist building-related companies in Oman to comply with environmental rules and avoid possible penalties and charges as environmental regulations become stricter all over the world.
- The reputation of the construction related institutions/companies may be enhanced by using sustainable construction waste management techniques, bringing in additional benefits.
- The lifespan of current landfills may be increased by redirecting construction waste elsewhere through recycling and reuse, which decreases the demand for new landfills.
- The use of green building techniques, such as the use of eco-friendly materials, energy-efficient designs, and water-saving technology, can be promoted via sustainable construction waste management.
- Construction trash may be recycled and reused to assist regional businesses that produce recycled goods, promoting economic expansion and job development.
- Builders and the public may experience improved health and safety conditions as a result of proper waste management. We can lessen the risk of accidents and exposure to hazardous materials by minimizing the quantity of waste and hazardous items on building sites.

Managing C&D waste and application of the 3Rs concept will significantly decrease the adverse effects on the environment and cut down on the production of C&D waste. Even after taking all necessary precautions and including many sustainability features before, during, and after construction, construction waste creation could not be eliminated. Recycling C&D waste is presently considered a very effective strategy for lowering the amount of waste delivered to landfills.

References

[1] E. O. W. Wong and R. C. P. Yip, “Promoting sustainable construction waste management in Hong Kong,” *Constr. Manag. Econ.*, vol. 22, no. 6, pp. 563–566, 2004, doi: 10.1080/0144619042000226270.

[2] P. D. A. C. Hauptfleisch, “Management and Innovation for a Sustainable Built Environment 20 – 23 June 2011, Amsterdam, The Netherlands ISBN: 9789052693958,” *Occup. Health (Auckl).*, no. June, 2011.

[3] J. N. Ismam and Z. Ismail, “Sustainable construction waste management strategic implementation model,” *WSEAS Trans. Environ. Dev.*, vol. 10, pp. 48–59, 2014.

[4] M. Ibrahim, “Estimating the sustainability returns of recycling construction waste from building projects,” *Sustain. Cities Soc.*, vol. 23, pp. 78–93, 2016, doi: 10.1016/j.scs.2016.03.005.

[5] R. E. C. Amaral *et al.*, “Waste management and operational energy for sustainable buildings: A review,” *Sustain.*, vol. 12, no. 13, 2020, doi: 10.3390/su12135337.

[6] A. T. W. Yu, I. Wong, Z. Wu, and C. S. Poon, “Strategies for effective waste reduction and management of building construction projects in highly urbanized cities— a case study of hong kong,” *Buildings*, vol. 11, no. 5, pp. 1–14, 2021, doi: 10.3390/buildings11050214.

[7] M. Mohammed, N. Shafiq, N. A. W. Abdallah, M. Ayoub, and A. Haruna, “A review on achieving sustainable construction waste management through application of 3R (reduction, reuse, recycling): A lifecycle approach,” *IOP Conf. Ser. Earth Environ. Sci.*, vol. 476, no. 1, 2020, doi: 10.1088/1755-1315/476/1/012010.

[8] I. M. C. S. Illankoon and W. Lu, “Cost implications of obtaining construction waste management-related credits in green building,” *Waste Manag.*, vol. 102, pp. 722–731, 2020, doi: 10.1016/j.wasman.2019.11.024.

[9] O. K. M. Ouda, H. P. Peterson, M. Rehan, Y. Sadef, J. M. Alghazo, and A. S. Nizami, “A Case Study of Sustainable Construction Waste Management in Saudi Arabia,” *Waste and Biomass Valorization*, vol. 9, no. 12, pp. 2541–2555, 2018, doi: 10.1007/s12649-017-0174-9.

[10] R. M. Gavilan and L. E. Bernold, “Source Evaluation of Solid Waste in Building Construction,” *J. Constr. Eng. Manag.*, vol. 120, no. 3, pp. 536–552, 1994, doi: 10.1061/(asce)0733-9364(1994)120:3(536).

[11] G. A. Bekr, “Study of the Causes and Magnitude of Wastage of Materials on Construction Sites in Jordan,” *J. Constr. Eng.*, vol. 2014, pp. 1–6, 2014, doi: 10.1155/2014/283298.

[12] C. Luangcharoenrat, S. Intrachooto, V. Peansupap, and W. Sutthinarakorn, “Factors influencing construction waste generation in building construction: Thailand’s perspective,” *Sustain.*, vol. 11, no. 13, 2019, doi: 10.3390/su11133638.

[13] M. Mohammed *et al.*, “Modeling of 3r (Reduce, reuse and recycle) for sustainable construction waste reduction: A partial least squares structural equation modeling (pls-sem),” *Sustain.*, vol. 13, no. 19, pp. 1–22, 2021, doi: 10.3390/su131910660.

[14] M. Mawed, M. S. Al Nuaimi, and G. Kashawni, “Construction And Demolition Waste Management In The Uae: Application And Obstacles,” *Int. J. GEOMATE*, vol. 18, no. 70, pp. 235–245, 2020, doi: 10.21660/2020.70.45101.

[15] M. M. Omer, R. A. Rahman, and S. Almutairi, “Strategies for Enhancing Construction Waste Recycling: A Usability Analysis,” *Sustain.*, vol. 14, no. 10, pp. 1–18, 2022, doi: 10.3390/su14105907.

[16] M. T. Newaz, P. Davis, W. Sher, and L. Simon, “Factors affecting construction waste management streams in Australia,” *Int. J. Constr. Manag.*, vol. 22, no. 13, pp. 2625–2633, 2022, doi: 10.1080/15623599.2020.1815122.

AN OVERVIEW OF PREDICTIVE MODELS OF CHLORIDE PENETRATION IN CONCRETE

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Abstract

Corrosion of reinforcement has a major impact on structural performances and service life. This is especially pronounced in reinforced concrete structures exposed to the marine environment, whose degradation is accelerated by chloride penetration. Therefore, the process of chloride penetration is one of the most important parameters when designing reinforced concrete structures, predicting their service life, and planning remedial measures and maintenance. Engineering calculation models can be divided into empirical and physical models, based on different physical expressions depending on the dominant transport mechanism or their interdependent combination. Different numerical and analytical methods are used to solve them. Also, we distinguish deterministic and probabilistic approaches to modeling. The first model of predicting chloride penetration in concrete was presented by Collepardi in 1970. Since then, the model has been significantly improved and developed into sophisticated models, most of which take Fick's laws of diffusion as a starting point. Today's models often encounter limitations and unreliability in use and long-term predictions due to the lack of understanding of the combination of transport mechanisms under real exposure conditions, the time dependence of the apparent diffusion coefficient, quality long-term data and the determination of boundary conditions. This paper presents an overview of models aimed to predict the penetration of chlorides in concrete, with an emphasis on transport mechanisms by diffusion and sorption, or their combination.

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Keywords: chlorides, diffusion, models, sorption, transport mechanisms.

1. Introduction

Corrosion of reinforcement has a great influence on structural performance and durability. This is especially pronounced in reinforced concrete structures exposed to the marine environment, whose degradation is accelerated by chloride penetration. The process of chloride penetration, its separation into individual transport mechanisms or their interdependent combination, is one of the most important parameters when designing reinforced concrete structures, as well as planning remedial measures and maintenance [1]. The water content in the pores of concrete, but also in the environment that surrounds it, has the greatest influence on transport mechanisms and degradation phenomena in concrete. Pores filled with water hinder the transport of the gaseous phase (diffusion) and facilitate the transport of the liquid phase (diffusion, sorption, convection). Concrete damage can be caused by water itself or by substances dissolved in water. Many molecules dissociate into ions of opposite charges when in solution. The water itself will move with the ions in it or the ions can move through the water (convection) [2, 3, 4]. Gradients of moisture content, pressure, electric potential, and concentration of substances, as well as stresses and various environmental conditions (e.g., temperature, precipitation) disrupt the state of fluid balance in the pores, and fluid transport occurs to re-establish the balance. The process of fluid transport is generally described in terms of sorption (absorption, adsorption), diffusion, flow under the pressure (permeation) and migration because of an electric field [4, 5]. It is important to mention the ion binding process, which can affect the transport mechanisms. The binding of chlorides can help in preventing or delaying their activation and corrosion of reinforcement because only free chlorides, available for transport, initiate corrosion [1]. This paper presents an overview of models aimed to predict the penetration of chlorides in concrete, with an emphasis on transport mechanisms by diffusion and sorption, i.e., capillary sorption, or their combination.

2. Models

Engineering calculation models can be divided into empirical and physical, based on the dominant transport mechanism or their interdependent combination. Numerical and analytical methods are used to solve them. Empirical and physical models need huge data bases and quantification of large number of material and environmental parameters [6]. Also, it can be distinguished deterministic and probabilistic approaches to modeling (calculation of the service life of the structure). The main characteristic of the deterministic approach is the reliability of the determined values of the action of the load and the resistance of the structure, and as a result the absolute value of the service life of the structure emerges. The probabilistic approach adopts the basic parameters in the calculation process as random, stochastic values, and follows the philosophy of calculation of structural load-bearing capacity, that is, the "load-resistance" calculation method with safety factors [7, 8]. Empirical models entail an analytical or numerical solution of Fick's second law of diffusion, including an error function solution; for example, Duracrete, Light Con, Bamforth model. Physical models in most cases include the numerical solution of Fick's first law of diffusion and the Nernst-Planck equation, i.e., separate expressions for different transport mechanisms or their combination; for example, ClinConc, MsDiff, Stadium model [7, 9]. The first model for predicting chloride penetration into concrete, presented by Collepardi in 1970., was based on the Fick's laws of diffusion to model chloride penetration from de-icing salts. The model was used for 20 years before it was realized that the main parameter, the apparent chloride diffusion coefficient, is not a material property. Since then, the model has been significantly improved and developed. The most common problem in modeling chloride penetration into concrete is the lack of understanding of the combination of transport mechanisms under real exposure conditions, time dependence of the apparent diffusion coefficient, quality long-term data and determination of boundary conditions [6, 7, 9].

2.1. Diffusion

Diffusion is the predominant transport mechanism in concrete submerged in water [1, 10]. Diffusion is described by Fick's laws, and the main parameter is the diffusion coefficient (*D*). Therefore, Fick's first law given by Eq. (1), is used to describe stationary diffusion, and Fick's second law given by Eq. (2), is used to describe non-stationary diffusion, which is more likely in concrete. Additionally, an error function solution, with initial and boundary conditions usually set as $C(x, t = 0) = 0$ and $C(x = 0, t) = Cs$, is given by Eq. (3):

$$J = -D\frac{\partial C}{\partial x} \tag{1}$$

$$\frac{\partial C}{\partial t} = D\frac{\partial^2 C}{\partial x^2} \tag{2}$$

Where *J* stands for the flow representing the rate of substance transport per unit area perpendicular to the *x* direction, *D* is the diffusion coefficient, $\partial C/\partial x$ is the concentration gradient, where *C* is the concentration of the diffusing substance (chlorides) and *t* presents diffusion time [6, 11].

$$\frac{C}{C_S} = 1 - erf\left(\frac{x}{2\sqrt{D \times t}}\right) \tag{3}$$

Eq. (3), as previously stated, includes an error function (*erf*) and *Cs* as the surface concentration of chlorides. Eq. (3) is valid in the case of constant diffusion coefficients and surface concentration of chlorides. In Fick's laws, there are two diffusion coefficients, apparent and real, different due to the influence of ion binding. Collepardi et. al used an error function solution to fit measured chloride profiles and derived the diffusion coefficient and surface concentration of chlorides for several cement pastes and laboratory exposure conditions.

By solving Fick's second law, which would describe chloride penetration into concrete, the mass conservation equation for chlorides, which extends Fick's second law of diffusion, is considered. Thus, there are two options: 1.) a mass balance of chlorides in the pore solution or 2.) a mass balance of the total amount of chlorides in a unit volume of concrete. The first alternative requires a separate term for the binding of chlorides to the matrix:

$$\frac{\partial c}{\partial t} = -\frac{\partial J}{\partial x} - \frac{\partial c_b}{\partial t} \tag{4}$$

$$\frac{\partial C}{\partial t} = -\frac{\partial J}{\partial x} \tag{5}$$

In Eq. (4) c is the concentration of chlorides in the pore solution and c_b is the amount of bound chlorides, while in Eq. (5) C presents the total amount of chlorides, all expressed per volume of concrete. By inserting Fick's first law, given by Eq. (1), with c as the chloride concentration and D_{F1} as the diffusion coefficient, into the mass balance equation, given by Eq. (5), it is obtained:

$$\frac{\partial C}{\partial t} = -\frac{\partial J}{\partial x} = D_{F1}\frac{\partial^2 c}{\partial x^2} \tag{6}$$

Eq. (6) is not identical to Fick's second law, given by Eq. (2), but a comparison gives a relationship between the two diffusion coefficients (real D_{F1} and apparent D_{F2},). Two diffusion coefficients are related by the chloride binding capacity dC/dc (if c instead is expressed per volume of pore solution, a factor equal to the porosity must be included in the denominator), as shown in Eq. (7):

$$D_{F2} = \frac{D_{F1}}{\frac{dC}{dc}} \tag{7}$$

If the diffusion coefficient in Fick's first law and the binding capacity are assumed constants, Fick's second law is obtained. Apparent diffusion coefficient D_{F2} is a measure of the diffusion strength of chlorides in the concrete pore solution, it is not a material property, and it decreases with time, so it cannot be constant as previously assumed. That was discovered about 20 years after Collepardi's model and since then an error function solution is used exclusively with the apparent diffusion coefficient, $D_{F2} = D_a$, in the exposure time interval (t_{a0}, t). Such a time dependence of the diffusion coefficient is given by Eq. (8):

$$D_a(t) = D_a(t_{a0}, t) = D_{a0} \times \left(\frac{t_{a0}}{t}\right)^{\alpha} \tag{8}$$

where t is the age of the concrete, t_{a0} is a reference period of exposure, α is the "aging exponent" and D_{a0} is the apparent diffusion coefficient at time t_{a0} and it cannot be determined directly, but it is necessary to know a series of chloride profiles for different exposure times. D_{a0} and α are merely looked upon as parameters that must be quantified from exposure data [6]. To include the time dependency of c_s, Mejlbro et al. (2008) proposed Mejlbro-Psi function Ψp instead of an error function. If Eq. (3) is written in the following form of Eq. (9):

$$\frac{c(x,t) - c_i}{c_S - c_i} = erf \times c\left(\frac{x}{2\sqrt{D_a \times t}}\right) \tag{9}$$

Mejlbro's *Ψp* function is given by Eq. (10):

$$\frac{c(x,t) - c_i}{c_S - c_i} = \Psi p\left(\frac{x}{2\sqrt{D_a \times t}}\right) \tag{10}$$

where c_i represents the initial concentration of chlorides in a semi-infinite medium, while c (x, t) represents the chlorides concentration per concrete depth (x) in the exposure time (t), and which can be determined by above given equation [7]. The ion binding capacity *dC/dc* means the capacity of the material to bind chlorides when their concentration changes. Binding is described by isotherms, and their slope represents the binding capacity. It depends on the concentration of chlorides, and in some cases it can be considered constant. It reaches infinite or high values at very low concentrations of chlorides, and it is believed that at high concentrations it tends to be zero [1]. The total amount of chlorides in concrete consists of bound and free chlorides, and their sum represents the total chloride content in concrete. To determine the profile of free chlorides, binding isotherms, usually built into models, are used. Two isotherms are mainly used – Freundlich's given by Eq. (11), and the Langmuir's given by Eq. (12). Freundlich isotherm was proposed in 1909 by German–American physical chemist H. M. F. Freundlich that relates adsorption of a quantity of gas adsorbed by unit mass of solid adsorbent with pressure. In 1916, I. Langmuir proposed his theoretical model for the variation of adsorption with pressure [6, 7].

$$c_b = \alpha \times C^{\beta} \tag{11}$$

$$c_b = \frac{\alpha \times C}{w(1+\beta \times C)} \tag{12}$$

In Eqs. (11) and (12) the C represents free chlorides, c_b the bound chlorides, w the water content, and α and β are the constants. Chloride binding can reduce the diffusion coefficient. It is important to mention that not only chlorides are present in the concrete pore solution, but also other ionic species that can affect each other. The Multi-Species Theory (MST), based on Fick's laws of diffusion, treats chlorides as molecules although they are actually charged particles or ions. Therefore, such charged particles interact with each other, positively or negatively charged particles, according to the principle of electroneutrality, given by Eq. (13) as follows:

$$\Sigma_{i=0}^{n} C_i z_i = 0 \tag{13}$$

In Eq. (13) C_i stands for the charged species (e.g., Cl^-, Na^+) present in the porous solution, and Z_i stands for the valance number of the species. While Fick's laws are essentially predicted for the transport of molecular species, the transport of ionic species such as chlorides is calculated according to the Nernst-Planck equation, given by Eq. (14), which implies the equation of conservation of mass, and describes the influence of the ionic concentration gradient, the moisture gradient and the influence of the electric field on the flow of chemical species, especially ions:

$$J_i = -D_i \frac{\partial C_i}{\partial x} - \frac{Z_i F}{RT} D_i C_i \frac{\partial E}{\partial x} + C_i V_i \tag{14}$$

In Eq. (14), R defines the ideal gas constant, T is the temperature, F is the Faraday's constant, V_i is the convection velocity and $\partial E/\partial x$ represents the electrical potential gradient. The first term of the Eq. (14) represents the flux due to diffusion, the second term denotes flux due to electro-migration and the third term due to moisture or pressure gradient (convection). Considering the situation where there is no convection, Eq. (14) is written without the last term C_iV_i [7].

2.2. Capillary sorption

Sorption is defined as chemical mutual incorporation, adhesion or absorption of substances into each other. In the case of concrete, we are talking about the capillary sorption of fluids into the unsaturated and partially saturated pores of the concrete. This is most often present in concrete in the splash or tidal zone. Capillary sorption refers to the movement of water through small pores in concrete, in the absence of externally applied pressure, and is the result of surface interactions between water and concrete pore walls. When water comes into contact with the porous surface of concrete, it is quickly absorbed due to the negative pressure in the pores caused by capillary action. The more porous the concrete, the faster it will absorb more water [4, 12]. Capillary activity depends on the viscosity, density and surface tension of the liquid, as well as the pore radius and the contact angle between the liquid and the pore wall. In general, sorption is determined depending on the depth of fluid penetration, and is described by the Eq. (15) as follows:

$$x = S\sqrt{t} \qquad (15)$$

where x presents the depth of fluid penetration, S presents the sorption constant, and t presents the sorption time [12]. I.e., equations (16) and (17) as follows:

$$\Delta W = A\sqrt{t} \qquad (16)$$

$$A = \Psi p\sqrt{\frac{r_{eff} \times \sigma \times cos\theta}{2\eta}} \qquad (17)$$

are given to determine the amount of absorbed water per unit area of concrete (ΔW) in the sorption time (t). In Eqs. (16) and (17), A presents capillary sorption coefficient. The capillary sorption coefficient describes the capillary activity and is calculated by Eq. (17), where Ψ is the water capacity of the porous material (capillary potential), ρ is the water density, r_{eff} is the effective pore radius that takes into account the pore size distribution, σ is the surface tension, Θ is the contact angle, and η is the viscosity [13, 14].

2.3. Combination of transport processes

Attempts to understand water transport mechanisms in a broader sense can be divided into experimental approaches, numerical simulations and analytical methods. When modeling (numerical simulation) capillary sorption, it is possible to take into account two levels of the transport: macroscopic and microscopic. Models based on the macroscopic level take into account the various thermal variation as well as hydrous and ionic movements, while those based on the microscopic level (e.g., models Stadium, MsDiff, Masi, Shin and Schmidt-Döhl) consider the flow of ions and their chemical balance in the concrete. The chemical reactions are considered only through parameters simulating the chemical effects on transport mechanisms (e.g., models Roelfstra, TransChlor, ClincConc, Meijers, Saetta and Ishida). The TransChlor theoretical one-dimensional model is an original model to address chlorides movement with water in concrete and to consider microclimates reconstituted from real climates. The TransChlor model is intended for saturated and unsaturated conditions in concrete, and considers the thermal diffusion process and the hydrous transport by capillarity suction and vapour diffusion as a function of the carbonation state, while simulating chloride ion transport in concrete. The model basically uses Fick's laws of diffusion for water vapour transport, thermal diffusion, and chloride ion diffusion in water, as well as the kinetics of phenomena and the associated kinetic equation for the transport of water by capillary absorption, which is transformed into convection - the movement of chloride ions with water [15, 16].

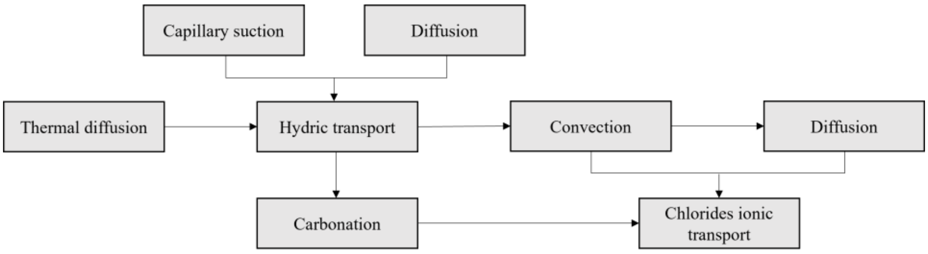

Figure 1. Schematization of transport model TransChlor [16].

Following model's equations are given by Eqs. (18), (19), (20), (21), (22), and (23):

$$\frac{\partial T}{\partial t} = div\left(\frac{\lambda_T(T,w)}{c_T(w)} \cdot \overrightarrow{grad(T)}\right) \tag{18}$$

$$\frac{\partial h_r}{\partial t} = div\left(D_h(T,h_r) \cdot \overrightarrow{grad(h_r)}\right) - \overrightarrow{D_{cap}}\left(t_{contact}, h_r, \frac{E}{C}, T\right) \circ \overrightarrow{grad(h_r)} \tag{19}$$

$$D_{cap} = D_{cap,t0} \cdot \left(\alpha_c + \frac{(1-\alpha_c)}{1+\left(\frac{1-t/10}{1+t_c}\right)^4}\right) \tag{20}$$

$$x_c = \sqrt{\frac{2 \cdot [CO_2] \cdot D_{e,CO_2}}{[Ca(OH)_2] + 3 \cdot [CSH]}} \cdot \sqrt{t} \tag{21}$$

$$\frac{\partial C}{\partial t} = div\left(R_{Cl} \cdot c_f \cdot D_h \cdot \overrightarrow{grad(h_r)} + w(h_r,T) \cdot D_{Cl} \cdot \overrightarrow{grad(C)}\right) + R_{Cl} \cdot c_f \cdot \left(\overrightarrow{D_{cap}} \circ \overrightarrow{grad(h_r)}\right) \tag{22}$$

$$C = c_f \cdot w + c_f^{\beta} \cdot \gamma \tag{23}$$

Eq. (18) describes the thermal diffusion process, where the specific heat capacity, c_T depends on moisture content, w, while the thermal conductivity, λ_T, is a function of moisture content, w, and temperature, T. In Eq. (19) hydrous transport is modelled by vapour diffusion, D_h, and water capillary, D_{cap}, coefficients. Vapour transport is a function of the temperature, T, and the moisture content, w. The temperature effect is described by means of the Arrhenius law. Water transport is a function of the concrete temperature, T, the moisture content, w, the pore humidity, h_r, and the duration of contact of concrete with water, $t_{contact}$. The capillarity coefficient, D_{cap}, of water is calculated according to Eq. (20), where the coefficients α_c and t_c were obtained by experimental calibrations on specific materials. The carbon dioxide, CO_2, transport governs the carbonation progression in concrete. The extent of carbonated concrete is required to determine the amount of chlorides absorbed by the cement paste. Concrete carbonation depth, x_c, expressed by Eq. (21), is obtained by considering the moisture content, the concrete permeability to CO_2 and the chemical carbonation reaction rate. The external conditions are represented by the molar carbon dioxide concentration *[CO_2]*. The carbonation reaction rate is described by the molar concentrations of calcium hydroxide *[$Ca(OH)_2$]* and calcium silicate hydrate *[CSH]*. The concrete carbon dioxide diffusion coefficient, $D_{e,CO2}$, takes into account the concrete permeability and the moisture content evolution in the concrete pores. The transport of chlorides following Eq. (22) is a function of the chloride diffusion through the pore water defined by moisture content, *w*, and the movement of entrained chlorides desolved in water moving through the concrete described by Eq. (19). This phenomenon is referred to as convection. The retardation of the chlorides front with respect to the convection induced water movement is taken into account by including the retardation coefficient, R_{Cl}. The chlorides bound in the cement paste, c_b, are distinguished from the free chlorides moving through the concrete, c_f. The relation between total amount of chlorides *C*, c_f and c_b is given by Eq. (23), including the Freundlich isotherm with constant parameters *β* and *γ*. Chloride diffusion coefficient in water, D_{Cl}, varies with the temperature, following the Arrhenius law. This describes the convection-diffusion model [15, 16].

Table 1. Combined transport processes models [17].

Name/person	Model
Iqbal and Ishida	Advective-diffusive model considering chloride transport coupled with moisture migration, further conducted a systematic experimental verification of moisture conductivity model
Li and Li	Global hydroionic model of drying-wetting cycle incorporating the diffusion-convection of chlorides in pore solution, matrix binding, and the influence of salt on the characteristic curve of moisture transport
Yu et al.	Chloride diffusion coefficient model coupled with environmental factors (*T*, h_r, *t*) to describe the chloride diffusion in concrete based on Fick's 2nd law, further conducted the correlation analysis of chloride ingress into concrete between the field test and artificial simulated environment experiments
Sun et al.	Prediction model for chloride transport coupled with the migration of water vapor and seepage of liquid water in unsaturated concrete under drying-wetting condition
Huang et al.	Pore - size distribution model to propose the numerical approach for describing moisture transport in concrete
Šavija et al.	2D lattice model capable of simulating rapid chloride transport in concrete under external electric field, and further discussed influence of concrete material heterogeneity and cracking on the transport properties
Wang et al.	2D mesoscale lattice network model developed on the basis of Voronoi tessellation was adopted to predict the behavior of water and chloride transport in cracked-unsaturated concrete under drying-wetting alternation condition
Zhao et al.	COMSOL Multiphysics software to investigate the influence of convection and diffusion on chloride transport in cement mortar during drying process, and the numerical simulation of chloride transport validated through experiments (capillary absorption and free diffusion test, drying test)

3. Conclusion

Corrosion caused by the presence of chlorides in reinforced concrete structures is a common cause of their premature degradation. This phenomenon has a great economic and ecological impact, especially near coastal areas and marine environment. Many transport models considering diffusion, capillary sorption and convection have been proposed to describe the behavior of chloride penetration into saturated or unsaturated concrete, and then numerical modeling to investigate the process of chloride transport and diffusion coefficient has been conducted. Subsequently, many studies have been presented to address the influence of some dominating factors (environmental temperature, humidity fluctuation, load) on the behavior of chloride transport in concrete. In addition, some models of chloride transport coupled with enhanced moisture conductivity, exposure time, and environmental factors in unsaturated concrete have been accordingly established. This paper provides an overview of predictive models of chloride penetration in concrete, with an emphasis on transport mechanisms by diffusion and capillary sorption, or their combination.

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References

[1] L.O. Nillson, E. Poulsen, P. Sandberg, H.E. Sorensen, O. Klinghoffer, "Chloride penetration into concrete. Sate-of-the-Art, Transport processes, corrosion initiation, test methods and prediction models," Hetek Technical Report No. 53, pp. 4–36, 1996, doi: 10.13140/RG.2.1.2771.7526.
[2] V. S. Ramachandran, "Concrete Science," Handbook of Analytical Techniques in Concrete Science and Technology, pp. 1–62, 2001, doi: 10.1016/b978-081551437-4.50004-7.
[3] P. A. Claisse, "Surface tests to determine transport properties of concrete – II: analytical models to calculate permeability," Transport Properties of Concrete, pp. 43–59, 2014, doi: 10.1533/9781782423195.43.
[4] L. Bertolini, B. Elsener, P. Pedeferri, E. Redaelli, and R. B. Polder, "Corrosion of Steel in Concrete," Apr. 2013, doi: 10.1002/9783527651696.
[5] M. Fenaux, "Modelling of chloride transport in non-saturated concrete : from microscale to macroscale", doi: 10.20868/upm.thesis.15285.
[6] L. Nilsson, "Concepts in chloride ingress modelling," Third International RILEM Workshop on Testing and Modelling Chloride Ingress into Concrete, 2005, doi: 10.1617/2912143578.003.
[7] A. Khitab, W. Anwar, and M. T. Arshad, "Predictive Models of Chloride Penetration in concrete: An Overview," MUST Journal of Engineering and Applied Sciences, vol. 1, no. 1, pp. 1–14, Mar. 2017, doi: 10.22496/mjeas20170103.
[8] I. Oslaković Stipanović, " Measuring and prediction of chlorides transport in concrete," Doctoral Thesis, Faculty of Civil Engineering, Zagreb, 2009.
[9] L. Nilsson, "Concepts in chloride ingress modelling," Third International RILEM Workshop on Testing and Modelling Chloride Ingress into Concrete, 2005, doi: 10.1617/2912143578.003.
[10] M. Otieno, H. Beushausen, and M. Alexander, "Chloride-induced corrosion of steel in cracked concrete – Part I: Experimental studies under accelerated and natural marine environments," Cement and Concrete Research, vol. 79, pp. 373–385, Jan. 2016, doi: 10.1016/j.cemconres.2015.08.009.
[11] J. Crank, N. R. McFarlane, J. C. Newby, G. D. Paterson, and J. B. Pedley, "Introduction to the Mathematics of Diffusion," Diffusion Processes in Environmental Systems, pp. 33–60, 1981, doi: 10.1007/978-1-349-05825-9_3.
[12] D. Bjegović, N. Štirmer, "Teorija I tehnologija betona," University Textbook, 2015.
[13] P. Zhang, F. H. Wittmann, and T. J. Zhao, "Capillary Suction of and Chloride Penetration into Integral Water Repellent Concrete / Kapillare Saugfähigkeit und Eindringen von Chloriden in integral hydrophobierten Beton," Restoration of Buildings and Monuments, vol. 15, no. 3, pp. 187–194, Jun. 2009, doi: 10.1515/rbm-2009-6292.
[14] C. Honglei, J. Zuquan, Z. Tiejun, W. Benzhen, L. Zhe, and L. Jian, "Capillary suction induced water absorption and chloride transport in non-saturated concrete: The influence of humidity, mineral admixtures and sulfate ions," Construction and Building Materials, vol. 236, p. 117581, Mar. 2020, doi: 10.1016/j.conbuildmat.2019.117581.
[15] D. Conciatori, H. Sadouki, and E. Brühwiler, "Capillary suction and diffusion model for chloride ingress into concrete," Cement and Concrete Research, vol. 38, no. 12, pp. 1401–1408, Dec. 2008, doi: 10.1016/j.cemconres.2008.06.006.
[16] D. Conciatori, F. Laferrière, and E. Brühwiler, "Comprehensive modeling of chloride ion and water ingress into concrete considering thermal and carbonation state for real climate," Cement and Concrete Research, vol. 40, no. 1, pp. 109–118, Jan. 2010, doi: 10.1016/j.cemconres.2009.08.007.
[17] J. Bao, R. Zheng, J. Wei, P. Zhang, S. Xue, and Z. Liu, "Numerical and experimental investigation of coupled capillary suction and chloride penetration in unsaturated concrete under cyclic drying-wetting condition," Journal of Building Engineering, vol. 51, p. 104273, Jul. 2022, doi: 10.1016/j.jobe.2022.104273.

REDUCTION OF CARBON EMISSIONS IN THE CONSTRUCTION INDUSTRY USING LEAN PRACTICES

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Abstract

Global warming is a significant issue on a global level, and the construction industry is a major contributor to the problem. The industry is responsible for approximately 38% of total global carbon emissions, with 13% of those emissions coming from the stages of construction and demolition. While many studies focus on reducing emissions during the exploitation phase, this paper proposes a reduction in carbon emissions during the construction phase by implementing the Lean philosophy. By eliminating waste and losses, including physical waste, overproduction, overprocessing, design errors, and excess transportation, the carbon reduction caused by burning fossil fuels is knowingly affected. By implementing Lean principles in construction phases, the construction industry can achieve direct reduction of greenhouse gases, primarily CO2. The paper presents eight recommendations for carbon reduction, recognized in the literature as Lean principles, including the use of low-carbon and recycled materials, optimizing design solutions, achieving more efficient construction processes, and utilizing renewable energy sources. By implementing these recommendations, the construction industry can significantly reduce its carbon footprint and contribute to the achievement of sustainable development goals.

Keywords: carbon emissions, lean construction, SDGs, waste.

1. Introduction

The release of carbon dioxide (CO_2) into the atmosphere is a major contributor to global warming and is considered one of the most critical environmental concerns [1]. Burning fossil fuels accounts for 65% of all greenhouse gas emissions, with other gases such as methane, nitrous oxide, and fluorinated gases also playing a role. Therefore, it has become a top priority to reduce emissions in all industries. Figure 1 illustrates the worldwide distribution of greenhouse gas emissions.

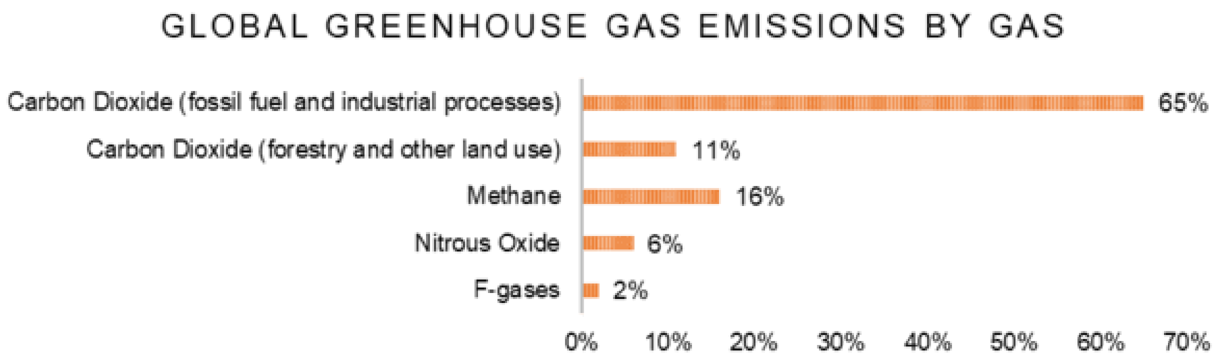

Fig. 1. Distribution of global greenhouse gas emissions [2]

The release of carbon dioxide has a significant impact on achieving the United Nations' Sustainable Development Goals (SDGs). Carbon emissions contribute to climate change, which is one of the most significant threats to achieving these goals. Climate change can lead to the depletion of natural resources, loss of biodiversity, food insecurity, and negative impacts on human health.

The construction industry is a significant contributor to the emission of carbon dioxide (CO_2) throughout various stages of a project. This is primarily due to the reliance on burning fossil fuels for the energy required during the production processes, as well as indirect emissions from electricity consumption [3], [4]. According to the Global status report [5], the construction industry has recorded the highest levels of CO_2 emissions, accounting for 38% of total emissions worldwide. The remaining 62% is attributed to traffic and other industries (Fig. 2). This data highlights the urgency for proposals aimed at reducing carbon emissions within the construction sector.

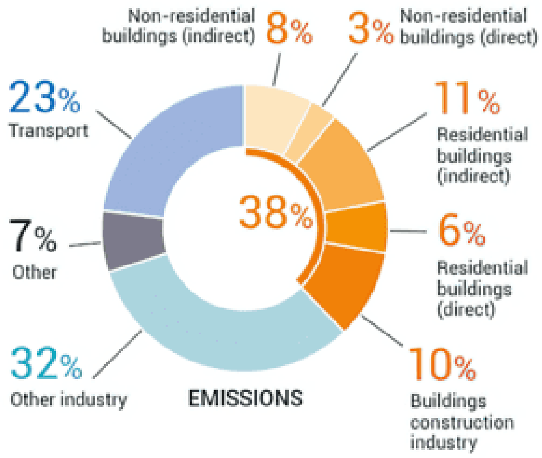

Fig. 2. Global share of emissions in construction [5]

The carbon emissions generated during the construction and demolition phases are commonly referred to as embodied carbon, which encompasses activities such as raw material extraction, production of building materials, transportation, installation, and eventual demolition of the building. This type of carbon represents the total amount of carbon incorporated into the construction process [6]. On the other hand, operational carbon emissions result from the building's operational phase, including activities such as heating, cooling, and maintenance. Embodied carbon accounts for 13% of total emissions, while operational carbon accounts for 27% [6]. These findings suggest the need to consider both embodied and operational carbon emissions in the overall carbon footprint of buildings to effectively address the carbon reduction goals in the construction industry.

Fig. 3. Carbon emission in different project stages [6]

While many researchers focus on reducing emissions during the maintenance phase of building exploitation, it is equally important to investigate and propose strategies for reducing carbon emissions in all phases of the construction process. For certain types of facilities, such as warehouses, emissions generated during the construction phase can be significant since the operational phase may not require heating or cooling, resulting in lower CO_2 emissions. This paper aims to investigate and propose ways to reduce CO_2 emissions during the construction phase of buildings by utilizing Lean principles. By implementing Lean principles, construction efficiency can be improved through synchronized processes and waste elimination, which can have a positive impact on the environment [7] and moreover, in achieving SDGs. This approach directly contributes to reducing carbon emissions during the building construction phase and mitigating environmental damage.

2. Literature review

Peng [8] analyzed the carbon dioxide emission using a building life cycle assessment (LCA), that considered various stages, including design, material production, construction, maintenance and demolition. The findings indicated that 85% of carbon emissions originated from the maintenance and use phase of the building, while 13% came from the construction phase, and 2% from the demolition phase. A study conducted by Weigert et al. [9] shows that the most significant part of emissions is generated due to transportation during the construction phase, followed by emissions from the demolition process. Labaran et al. [10] contend that it is important to analyze carbon emissions during the demolition phase because significant amounts of CO_2 are released during the demolition, waste transportation and recycling.

Gomez et al. [11] conducted a comparative analysis of two projects with similar characteristics, one in which Lean principles were implemented and the the other in which they were not. The life cycle assessment (LCA) determined that by applying Lean principles, carbon emissions were reduced by up to 24%, and the negative impact on people's health during construction was reduced by up to 25%. Rezende et al. [12] conducted a case study implementing Lean and Green strategies. A comparison of reinforced concrete construction and light steel frame was made. The results indicated that the light steel frame construction had a 48% higher added value and emitted 8% fewer greenhouse gases during the building's life cycle compared to reinforced concrete construction. Furthermore, the steel structure was found to be 1.38 times more environmentally efficient than the concrete structure. These findings demonstrate the potential benefits of using Lean and Green strategies in construction, as they can result in reduced carbon emissions and improved environmental performance. Wu and Low [13] utilized Lean methodology to identify activities that do not add value to prefabricated production but contribute to increased carbon emissions.The results indicate that the level of carbon emissions reduction is most influenced by Lean principles such as continuous improvement (providing more alternatives to prefabricated products and the use of green building materials), the withdrawal system, and the transparency of information that ensures a smooth flow of production. Ghosh et al.[14] conducted a case study on producing and transporting drywall trade. They compared two cases, one in which traditional management methods were adopted and the other in which Lean techniques were applied to reduce waste. Then the results of that reduction were expressed through environmental benefits by measuring CO_2 reduction. By applying Lean techniques, the amount of waste was reduced by 6%, and greenhouse gas emissions were reduced by more than 7.5 $mtCO_2e$. Heravi et al.[15] implemented Lean techniques in the production and assembly process of steel frames to reduce energy consumption and CO_2 emissions. Life cycle assessment (LCA) estimated a reduction in energy consumption of up to 9.2%, while CO_2 emissions were reduced by 4.4% during production and assembly.

The literature review concluded that the Lean methodology significantly impacts reducing CO_2 emissions in the construction industry. These findings demonstrate the potential of Lean techniques in promoting sustainable construction practices that prioritize the efficient use of resources and reduce carbon emissions.

3. Lean construction

Lean construction is a widely adopted approach that aims to minimize waste and losses and maximize value in construction projects. The approach emphasizes waste reduction as it increases production capacity, as the total production capacity is a sum of work and waste [16].

The integration of Lean principles in the construction industry can significantly improve its performance by reducing waste from both technical and operational perspectives and improving teamwork by eliminating communication problems. Lean principles aim to analyze waste and losses resulting from all activities involved in the design, construction, and demolition/disassembly processes.

Lean principles promote a unique approach to construction management, which differs from typical modern practice. According to Lean principles, construction management involves establishing a clear set of goals for the delivery process, maximizing performance at the project level, designing the facility and planning the process in parallel, and applying control throughout the duration of the project. The principles emphasize the importance of developing teamwork and a willingness to shift the burden along supply chains, which only works when all participants' entire process and work are aligned. Additionally, project performance can only be individually optimized by considering and understanding the mutual influence of all project components [17].

Womack et al. [18] define three basic waste categories: muri, mura and muda. Muda is waste in the form of activities that do not add value and/or work that causes waste, as well as physical waste that occurs during the project and the life of the structure. Eight types of waste/loss (muda) are shown in Figure 4.

Fig. 4. Eight types of waste defined by [18]

Removing this category of the waste directly affects the reduction of emissions. By explicitly thinking about eliminating the unnecessary use of resources, the Lean approach can significantly reduce costs, improve competitiveness and, most importantly, achieve environmental performance goals simultaneously.

4. Recommendations for reducing CO_2 emissions

As previously noted, CO_2 emissions in the construction industry are mainly caused by the burning of fossil fuels at production sites and the consumption of electricity. However, it is also important to consider the emissions resulting from the production of construction materials and transportation of those materials both within and outside the construction site. The adoption of Lean approach can effectively identify opportunities to reduce greenhouse gas emissions in the construction industry by optimizing the use of resources and reducing waste. Based on the available literature, some recommendations for reducing carbon dioxide emissions through Lean principles in the construction industry are:

- **Eliminating waste and losses during the construction project** - By preventing excessive production of construction materials, elements or objects, CO_2 emissions from production processes will be reduced. Those production processes cause the consumption of electricity and the burning of fossil fuels to run equipment and machinery, which are the indirect and direct sources of emissions. Storing excessive amounts of materials and elements also leads to the need for warehouses, which generate direct emissions during construction and indirect emissions during maintenance. Reducing the need for additional transport, unnecessary movement and waiting on the project is crucial for reducing direct CO_2 emissions, as transport is one of the leading causes of global warming due to high emissions. Additionally, a lack of skills and knowledge among project participants is a significant cause of waste and losses during construction projects, leading to the occurrence of scrap and excessive processing in production processes, which also contribute to carbon emissions. By eliminating these types of waste and losses, the need to repeat production operations that cause CO_2 emissions can be minimized, ultimately reducing the carbon footprint of the construction industry. The implementation of Lean principles, such as just-in-time production and pull systems, can help reduce waste and losses, leading to more efficient construction practices that prioritize the sustainable use of resources and reduce carbon emissions.
- **Use of low-carbon materials -** The choice of building materials, especially the main structural elements that make up about 80% of the building, can significantly impact the amount of carbon dioxide emissions in construction. For example, a study by Cabeza et al. [19] analyzed the life cycle of concrete, steel, and wood frame construction and found that a concrete frame generates 44% more CO_2 emissions than a steel frame and 49% more than a wooden one. Another study by You et al. [20] compared the lifetime emissions of a reinforced concrete structure and a steel structure, finding that the reinforced concrete structure emitted 329.61 t of CO_2, while the steel structure emitted 315.79 t. The findings of these studies demonstrate that the choice of material directly affects the level of emissions, with some materials having a lower carbon footprint than others. Additionally, the homogeneity and method of connection of steel structural elements make them much easier to recycle or reuse compared to reinforced concrete elements, which can contribute to reductions in emissions through material circularity and the elimination of repeated production processes. According to researchers [21], [22], some low-carbon materials include low-carbon cement, wood, clay, straw, cork, bamboo, stone, rammed earth and sawdust. By prioritizing the use of low-carbon materials in construction, the industry can play a critical role in mitigating the impacts of global warming and contributing to a more sustainable future.
- **Better Improved design solution** - Optimizing the design of buildings to be compatible with the natural environment and conditions is a critical step in reducing carbon emissions in construction. One way to achieve this is by selecting low-carbon materials or materials that are sourced locally, which can reduce emissions associated with transportation. Furthermore, the adoption of structural systems that require minimal use of machinery during construction and can be dismantled and recycled or reused can also contribute to significant reductions in carbon emissions.
- **Use of recycled materials** – Cement production generates over 6% of the total CO_2 emissions [23]. Research by Shin and Kim [24] explored the use of recycled aggregates for non-structural building materials and found that it could reduce embodied carbon emissions for different types of buildings by up to 10%. Similarly, Costa and Ribeiro [25] were able to reduce CO2 emissions by up to 15% by replacing traditional raw materials for cement production with construction waste. The use of recycled materials has multiple benefits, including reducing waste in landfills and reducing CO_2 emissions. By prioritizing the use of recycled materials in construction, the industry can contribute to a more sustainable and circular economy while also mitigating the impacts of global warming.

- **Use of materials that can be found near the construction site** - This recommendation is directly related to the length of transportation of materials. Shortening the transport length reduces the need for transport machinery that causes direct CO_2 emissions by burning fossil fuels. Crishna et al. [26] investigated the differences in CO_2 emissions during the production of three different types of stone. The study results showed that stone production in Great Britain was more efficient in terms of CO_2 emissions than other countries included in the study. However, the authors note that significant emissions reductions can still be achieved by increasing production efficiency, shortening transportation, and using local materials, i.e. reducing the import of materials from other countries.
- **Improving the efficiency of the construction process** - Good planning and project management achieve efficiency in construction processes, i.e. reduction of waste (more efficient production of materials), shorter construction period (shortening of mechanization work), more efficient use of mechanization in construction processes, reduction of electricity consumption and others.
- **Use of prefabricated elements** - Jeong et al. [27] compared the emissions of a prefabricated column and a column constructed on-site, considering the stages of manufacture, transport and assembly. The research results showed that the CO_2 emissions of the prefabricated column were 72% higher because the emissions during the production phase of the prefabricated column were much higher. However, research conducted by Ji et al. [28] reduced total greenhouse gas emissions by 3.2%. The research included estimating total emissions during the construction of one prefabricated building and one building whose construction was on-site. Emissions which originate from production, transport and construction processes were analyzed. Research findings by Iodica et al. [29] showed that selective demolition and increased recycling reduce greenhouse gas emissions by 88%. A case study by Cui et al. [30] shows that demolishing an existing building and building a new one emits less carbon than rebuilding, renovating and conserving the building. Applying prefabricated systems would ensure the possibility of dismantling buildings and, therefore, reduce emissions that the previously mentioned authors observed through their research activities. The potential for further reduction of CO_2 emissions can be found by considering production processes in prefabrication.
- **Use of renewable energy sources** - Tan et al. [31] investigated the impact of using renewable energy sources to reduce CO_2 emissions. The study results showed that using renewable energy sources in China reduced emissions by 0.324% per capita. Renewable energy sources were found to have the greatest potential for reducing CO_2 emissions during the operational phase of a facility.

5. Conclusion

Global warming significantly impacts the deterioration of the quality of the environment, life on the planet and future generations. One of the industries that can significantly contribute to eliminating this problem is the construction industry because it is responsible for 38% of CO2 emissions on Earth. The Lean philosophy has shown to be an effective approach in reducing carbon emissions by eliminating waste, optimizing construction processes, using sustainable materials, and increasing quality and value. By implementing Lean principles in the construction phases, the goal is directly achieved, which is the reduction of gases with the greenhouse effect, the largest share of which is precisely CO_2. Carbon emissions are reduced by reducing all types of waste, errors and repairs on the construction site, transportation needs, optimizing the planning of construction projects, reusing materials/elements, using sustainable materials, and increasing quality and value. Through the analysis of studies and research, this paper presented eight recommendations for carbon reduction in the construction industry, which include eliminating waste during construction, using low-carbon and recycled materials, optimizing the design solution, using materials that are closer to the construction site, achieving more efficient construction processes, using prefabricated elements, and using renewable energy sources.

The directions of further research would focus on the possibility of reducing CO_2 emissions by applying Lean methodology in other phases of construction projects, as well as integrating BIM technology with the aim of easier implementation of Lean principles. By implementing these recommendations and further exploring new solutions, the construction industry can contribute to reducing CO_2 emissions and promoting a more sustainable future. Moreover, by implementing sustainable construction practices, such as utilizing renewable energy sources, reducing waste, and improving construction efficiency, the construction industry can significantly reduce its carbon footprint and contribute to the achievement of SDGs.

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References

[1] L. Farahzadi and M. Kioumarsi, “Application of machine learning initiatives and intelligent perspectives for CO2 emissions reduction in construction,” *J. Clean. Prod.*, vol. 384, no. November 2022, p. 135504, 2023, doi: 10.1016/j.jclepro.2022.135504.
[2] R. T. Venterea, “Climate Change 2007: Mitigation of Climate Change,” 2009. doi: 10.2134/jeq2008.0024br.
[3] Charles J. Kibert, “ESTABLISHING PRINCIPLES AND A MODEL FOR SUSTAINABLE CONSTRUCTION,” in *Sustainable Construction*, 1994, no. 16, pp. 3–12. [Online]. Available: https://www.irbnet.de/daten/iconda/CIB_DC24773.pdf
[4] U. S. E. P. A. EPA, “Lean & Energy Toolkit: Chapter 1,” 2022. https://www.epa.gov/sustainability/lean-energy-toolkit-chapter-1 (accessed Mar. 13, 2023).
[5] UNEP, “Towards a zero-emissions, efficient and resilient buildings and construction sector,” 2020. [Online]. Available: https://globalabc.org/sites/default/files/inline-files/2020 Buildings GSR_FULL REPORT.pdf
[6] Architecture 2030, “Why the built environment?” https://architecture2030.org/why-the-building-sector/ (accessed Feb. 19, 2023).
[7] F. Fu, J. Sun, and C. Pasquire, “Carbon Emission Assessment for Steel Structure Based on Lean Construction Process,” *J. Intell. Robot. Syst. Theory Appl.*, vol. 79, no. 3–4, pp. 401–416, 2015, doi: 10.1007/s10846-014-0106-x.
[8] C. Peng, “Calculation of a building’s life cycle carbon emissions based on Ecotect and building information modeling,” *J. Clean. Prod.*, vol. 112, pp. 453–465, 2016, doi: 10.1016/j.jclepro.2015.08.078.
[9] M. Weigert, O. Melnyk, L. Winkler, and J. Raab, “Carbon Emissions of Construction Processes on Urban Construction Sites,” *Sustain.*, vol. 14, no. 19, pp. 1–14, 2022, doi: 10.3390/su141912947.
[10] V. S. MATHUR, M. M. FAROUQ, and Y. H. LABARAN, “The carbon footprint of construction industry: A review of direct and indirect emission,” *J. Sustain. Constr. Mater. Technol.*, vol. 6, no. 3, pp. 101–115, 2021, doi: 10.29187/jscmt.2021.66.
[11] J.-L.-T. Cristian-Camilo Osorio-Gomez, William-Miguel Leon-Daza, Andres-Felipe Moggio-Bessolo, Angelica Ospina -Alvarado, “Lean Construction Impract on the Environmental Footprint of a Construction Project in Colombia: A Case Stady,” in *Construction Research Congress 2020*, 2020, pp. 379–387. doi: 10.1061/9780784482889.040.
[12] M. de Oliveira Rezende, M. R. M. Saade, A. O. Nunes, V. G. da Silva, V. A. S. Moris, and D. A. L. Silva, “A Lean and Green approach for the eco-efficiency assessment on construction sites: description and case study,” *Clean Technol. Environ. Policy*, vol. 24, no. 5, pp. 1535–1552, 2022, doi: 10.1007/s10098-021-02265-y.
[13] P. Wu and S. P. Low, “Lean Management and Low Carbon Emissions in Precast Concrete Factories in Singapore,” *J. Archit. Eng.*, vol. 18, no. 2, pp. 176–186, 2012, doi: 10.1061/(asce)ae.1943-5568.0000053.
[14] S. Ghosh, S. Bhattacharjee, P. Pishdad-Bozorgi, and R. Ganapathy, “A case study to examine environmental benefits of lean construction,” in *22nd Annual Conference of the International Group for Lean Construction: Understanding and Improving Project Based Production, IGLC 2014*, 2014, vol. 1, no. 405, pp. 133–144. [Online]. Available: https://iglcstorage.blob.core.windows.net/papers/attachment-f9b0342f-8961-4f93-93ec-1bae441c2888.pdf
[15] G. Heravi, M. Rostami, and M. F. Kebria, “Energy consumption and carbon emissions assessment of integrated production and erection of buildings’ pre-fabricated steel frames using lean techniques,” *J. Clean. Prod.*, vol. 253, p. 120045, 2020, doi: 10.1016/j.jclepro.2020.120045.
[16] T. S. Fidelis Emuze, *Value and Waste in Lean construction*, 1st ed. London, UK: Routledge, 2015. doi: https://doi.org/10.4324/9781315696713.
[17] G. A. Howell, “What is lean construction,” in *7th Annual Conference of the International Group for Lean Construction*, 1999, vol. 7, no. July, pp. 1–10. [Online]. Available: https://iglcstorage.blob.core.windows.net/papers/attachment-616a489a-8e13-46a6-85b3-34eedd72ac8b.pdf
[18] D. R. James P. Womack, Daniel T. Jones, *The Machine That Changed The World*, 1st Free P., no. 1. New York, USA: FREE PRESS, 2007.
[19] L. F. Cabeza, L. Rincón, V. Vilariño, G. Pérez, and A. Castell, “Life cycle assessment (LCA) and life cycle energy

analysis (LCEA) of buildings and the building sector: A review," *Renew. Sustain. Energy Rev.*, vol. 29, pp. 394–416, 2014, doi: 10.1016/j.rser.2013.08.037.

[20] Y. Y. Fang You, Dan Hu, Haitao Zhang, Zhen Guo, Yanhua Zhao, Bennan Wang, "Carbon emissions in the life cycle of urban building system in China-A case study of residential buildings," *Ecol. Complex.*, vol. 8, no. 2, pp. 201–212, 2011, doi: 10.1016/j.ecocom.2011.02.003.

[21] Y. H. Labaran, V. S. Mathur, S. U. Muhammad, and A. A. Musa, "Carbon footprint management: A review of construction industry," *Clean. Eng. Technol.*, vol. 9, no. May, p. 100531, 2022, doi: 10.1016/j.clet.2022.100531.

[22] L. F. Cabeza, C. Barreneche, L. Miró, J. M. Morera, E. Bartolí, and A. Inés Fernández, "Low carbon and low embodied energy materials in buildings: A review," *Renew. Sustain. Energy Rev.*, vol. 23, pp. 536–542, 2013, doi: 10.1016/j.rser.2013.03.017.

[23] J. Zhang, G. Liu, B. Chen, D. Song, J. Qi, and X. Liu, "Analysis of CO2 Emission for the cement manufacturing with alternative raw materials: A LCA-based framework," *Energy Procedia*, vol. 61, pp. 2541–2545, 2014, doi: 10.1016/j.egypro.2014.12.041.

[24] B. Shin and S. Kim, "CO2 emission and construction cost reduction effect in cases of recycled aggregate utilized for nonstructural building materials in South Korea," *J. Clean. Prod.*, vol. 360, no. November 2021, p. 131962, 2022, doi: 10.1016/j.jclepro.2022.131962.

[25] F. N. Costa and D. V. Ribeiro, "Reduction in CO2 emissions during production of cement, with partial replacement of traditional raw materials by civil construction waste (CCW)," *J. Clean. Prod.*, vol. 276, p. 123302, 2020, doi: 10.1016/j.jclepro.2020.123302.

[26] N. Crishna, P. F. G. Banfill, and S. Goodsir, "Embodied energy and CO2 in UK dimension stone," *Resour. Conserv. Recycl.*, vol. 55, no. 12, pp. 1265–1273, 2011, doi: 10.1016/j.resconrec.2011.06.014.

[27] J. Jeong *et al.*, "An integrated evaluation of productivity, cost and CO2 emission between prefabricated and conventional columns," *J. Clean. Prod.*, vol. 142, pp. 2393–2406, 2017, doi: 10.1016/j.jclepro.2016.11.035.

[28] Y. Ji, K. Li, G. Liu, A. Shrestha, and J. Jing, "Comparing greenhouse gas emissions of precast in-situ and conventional construction methods," *J. Clean. Prod.*, vol. 173, pp. 124–134, 2018, doi: 10.1016/j.jclepro.2016.07.143.

[29] S. Iodice, E. Garbarino, M. Cerreta, and D. Tonini, "Sustainability assessment of Construction and Demolition Waste management applied to an Italian case," *Waste Manag.*, vol. 128, pp. 83–98, 2021, doi: 10.1016/j.wasman.2021.04.031.

[30] W. Cui, J. Hong, G. Liu, K. Li, Y. Huang, and L. Zhang, "Co-benefits analysis of buildings based on different renewal strategies: The emergy-lca approach," *Int. J. Environ. Res. Public Health*, vol. 18, no. 2, pp. 1–23, 2021, doi: 10.3390/ijerph18020592.

[31] H. Tan, N. Iqbal, and Z. Wu, "Evaluating the impact of stakeholder engagement for renewable energy sources and economic growth for CO2 emission," *Renew. Energy*, vol. 198, no. August, pp. 999–1007, 2022, doi: 10.1016/j.renene.2022.08.039.

EMPIRICAL STUDY ON COST RISK IN INTERNATIONAL CONSTRUCTION PROJECT

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Abstract
Since the multidimensional uncertainties, the international construction market is a more risker market rather than domestic construction market. Sustainable business in the international market requires accurate project diagnosis and proactive response strategies through the risk assessment process and it is necessary to provide empirical risk evaluation data to support more accurate risk assessment in aspects of practice. This study, therefore, aims to analyze and provide risk evaluation data which contains key risk factors, risk impact and probability in aspects of cost performance. The 124 international construction projects conducted from Korean contractors were used in this study. The key risk factors were derived by comparing low-performance project and high-performance project in aspects of cost performance and the results are suggested by product types which are civil structure, building and plant. The study found that 'Insufficient period for construction completion', 'Weather and climate uncertainty' and 'IT based project management difficulties' are the high ranked risk factors regardless of product types. It also found that contract risk had the greatest impact on business in international market since lots of high ranked risk factors are belong to contract risk. The results of this study can be used as a reference data for practitioners to evaluate the risks of international construction projects and will support them successfully carry out the project through more accurate risk assessment based on past case data.

Peer-review under responsibility of the scientific committee of the Creative Construction Conference 2023.

Keywords: international construction, cost risk, risk evaluation data

1. Introduction

1.1. Research Background

Since the multidimensional uncertainties, the international construction market is a more risker market rather than domestic construction market [1]. Many construction contractors have entered international market in anticipation of high profitability based on the principle of the "high risk high return". Due to difficulties such as unfamiliar site condition, cultural difference, project complexity, insufficient contingency, however, it is difficult to guarantee high returns in the international market [2-4]. Many studies were conducted on risk management methods to successfully carry out international construction project. The author's previous study which is one of them dealt with the relation between risk management performance and project performance and the result showed that risk assessment performance which means risk assessment accuracy is the most important success factor to yield the high return rather than risk mitigation performance [5]. In order to carry out sustainable business in international markets, it is necessary to provide empirical risk evaluation data to support more accurate risk assessment. Therefore, this study aims to derive key risk factors by analyzing risk evaluation data of international construction projects as a pilot study for supporting more accurate risk assessment in practice. This study sought to provide more detailed information to practitioners by deriving key risk factors based on impact and probability by product types which are civil structure, building and plant.

1.2. Research Framework

The purpose of this study is to find out the key risk factors by comparing low-performance project (LPP) and high-performance project (HPP) in aspects of project cost and provide the empirical risk evaluation data which contains risk impact and probability. To achieve this purpose. this study conducted a structured questionnaire-surveys of 124 international construction projects. Through the surveys, cost impact data of 54 risk factors and the actual profitability data were collected. Second, international construction projects classified into three product type. And then these project groups classified into LPP and HPP based on profitability of each project. Lastly, Impact and probability of 54 risk factors were calculated for each group based on cost impact data collected from surveys. To test the difference of impact and probability between LPP and HPP, Mann-Whiney U test was conducted, and the key risk factors, finally, were derived by product type. Fig 1. Shows the overall research framework.

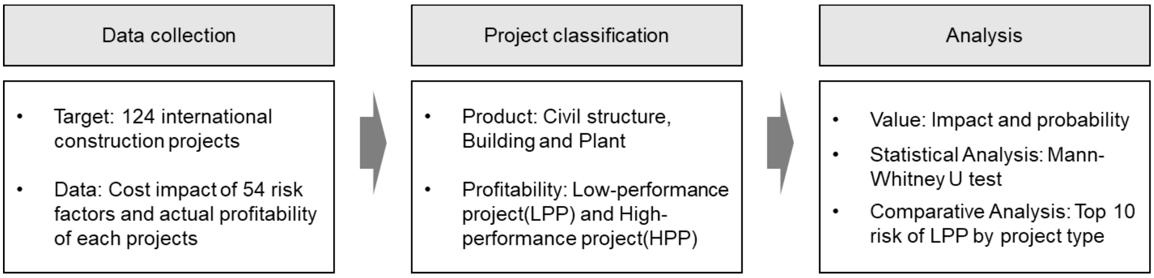

Fig. 1. Research framework

2. Methodology

2.1. Data collection

The 54 risk factors which are same as the authors' previous study [5,6] are used in this study. As shown in Table 1, the 54 risk factors grouped into 9 subcategories which are political risk, economical risk, infra and social risk, owner risk, contract risk, site risk, management risk, technical risk, and partner risk. These subcategories also grouped into 3 categories which are country risk, project risk and capability risk.

Table 1. Risk factors of international construction project [5,6]

Category	Code	Subcategory (# of risk factors)
Country risk	CP	Political risk (3)
	CE	Economical risk (3)
	CI	Infra and social risk (6)
Project risk	PO	Owner risk (5)
	PC	Contract risk (9)
	PS	Site risk (4)
Capability risk	CAM	Management risk (12)
	CAT	Technical risk (5)
	CAP	Partner risk (3)

Based on these factors, this study conducted questionnaire-surveys to 124 international construction projects which were performed by the Korean contractors. Through the questionnaire-surveys, the cost impact of each 54 risk factors and actual profitability of projects were collected. Especially, this study evaluated cost impact of risk factors as skewed seven-point Likert scale (Fig 2). Therefore, this study reflected both positive and negative effect of each risk factors on project cost performance.

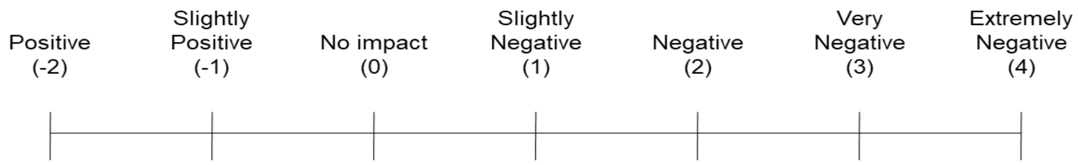

Fig. 2. Risk measurement scale

2.2. Project classification

This study aims to analyze the difference of risk impact and probability between low-performance project (LPP) and high-performance project (HPP) in aspects of cost performance. As a criterion for distinguishing LPP and HPP, actual profitability information collected through surveys was used. Using median value of the profitability, this study analyzed the cost impact data collected by dividing LPP and HPP for each of the three product types which are civil structure, building and plant.

2.3. Risk impact and probability

Based on result of questionnaire-surveys and project classification, the risk impact and risk probability were calculated for each project group. The impact of individual risk factors was calculated as the average of the evaluated cost impacts. The probability of individual risk factors was calculated on the assumption that risk did not occur when the cost impact was evaluated as zero (No impact). The summary of average risk impact and probability by each project group are as shown in Table 2.

Table 2. The summary of average risk impact and probability

Project profile		Total	LPP (<5%)	HPP (>5%)
Civil structure	# of project	67	37	30
	impact	0.299	0.582	0.017
	probability	33.0%	40.5%	25.5%
Building	# of project	33	15	18
	Impact	0.406	0.550	0.262
	probability	35.4%	39.4%	31.4%
Plant	# of project	24	16	8
	impact	0.095	0.181	0.009
	probability	30.3%	29.9%	30.6%

3. Analysis and Result

Since the data set was not satisfied the normality, this study used the Mann-Whitney U test to test the difference between LPP and HPP. The Mann-Whitney U test which is one of the non-parametric statistical analyses and it is used to compare differences between two independent groups when the dependent variable is either ordinal or continuous, but not normally distributed [7]. The key risk factors were derived as the top ranked factors of LPP in aspects of impact and probability. The results suggested as followed.

3.1. Civil structure

Table 3. shows the impact of top ranked risk factors in civil structure projects, where ‘Insufficient period for construction completion’ and ‘Weather and climate uncertainty’ ranked first, second in both LPP and HPP, posing the most and the second most degree of risk on both LPP and HPP. ‘Material supply difficulties in host country’, ‘Administrative approval and licensing delays’, ‘Imperfect institution related to construction’ and ‘Unfavorable tax and tariff treaty’ showed similar rankings between LPP and HPP.

However, there was a significant difference in rankings between LPP and HPP for ‘Uncertainty of inflation rate’ and ‘Insufficient time for bid preparation’. These two risk factors ranked high in LPP projects, indicating a substantial degree of risk on LPP. On the contrary, these two risk factors scored below zero in HPP, meaning that they had a positive impact on cost performance. Therefore, these two risk factors require intensive management to obtain high return in aspects of cost performance.

Table 3. Impact of top 10 risk factors in civil structure

Risk Factor	Code	LPP		HPP	
		Impact	Rank	Impact	Rank
Insufficient period for construction completion[b]	PC	1.703	1	0.600	1
Weather and climate uncertainty[b]	PS	1.361	2	0.467	2
Uncertainty of inflation rate[b]	CE	1.306	3	-0.067	33
IT based project management difficulties[b]	CAT	1.297	4	0.172	13
Material supply difficulties in host country[b]	CI	1.270	5	0.267	7
Administrative approval and licensing delays[b]	PO	1.194	6	0.333	5
Insufficient time for bid preparation[b]	PC	1.135	7	-0.167	44
Subcontractor supply difficulties in host country[b]	CI	1.135	7	0.267	7
Imperfect institution related to construction[b]	CP	1.108	9	0.172	13
Unfavorable tax and tariff treaty	PC	1.028	10	0.345	4

[a]Correlation is significance at the 0.1 level (two tailed), [b]Correlation is significance at the 0.05 level (two tailed)

Table 4. shows the probability of top ranked risk factors in civil structure projects. The probability of all top 10 risks in the LPP as more than 50%. ‘Weather and climate uncertainty ‘, ‘Insufficient period for construction completion’, ‘Uncertainty of inflation rate’, ‘IT based project management difficulties’ and ‘Insufficient time for bid preparation’ ranked high in both LPP and HPP. However, ‘Insufficient organizational management capability’, ‘Insufficient claim management capability’, ‘Imperfect institution related to construction’ and ‘Insufficient project management capability of employer’ ranked only high in LPP, not in HPP. To achieve high performance, practitioner should develop a response plan that mitigates the probability of these factors.

Table 4. Probability of top 10 risk factors in civil structure project

Risk Factor	Code	LPP		HPP	
		Probability	Rank	Probability	Rank
Insufficient organizational management capability[b]	CAM	69.4%	1	30.0%	20
Weather and climate uncertainty[a]	PS	63.9%	2	40.0%	4
Insufficient claim management capability[b]	CAM	63.9%	2	30.0%	20
Insufficient period for construction completion	PC	62.2%	4	46.7%	2
Uncertainty of inflation rate	CE	61.1%	5	50.0%	1
IT based project management difficulties[a]	CAT	59.5%	6	37.9%	6
Imperfect institution related to construction[b]	CP	56.8%	7	24.1%	31
Insufficient project management capability of employer[b]	PO	56.8%	7	26.7%	28
Administrative approval and licensing delays[a]	PO	55.6%	9	33.3%	15
Insufficient time for bid preparation	PC	54.1%	10	36.7%	8

[a]Correlation is significance at the 0.1 level (two tailed), [b]Correlation is significance at the 0.05 level (two tailed)

3.2. Building

Table 5. shows the impact of top 10 risk factors in building projects, where ‘Insufficient period for construction completion’, ‘Weather and climate uncertainty’, ‘Overall construction method difficulties’

and ‘Difference in culture, customs, and routines’ ranked high in both LPP and HPP. ‘Insufficient time for bid preparation’ and ‘JV's insufficient construction capability’ are the biggest difference in rank between LPP and HPP. Therefore, these two risk factors require intensive management to obtain high return in aspects of cost performance.

Table 5. Impact of top 10 risk factors in building

Risk Factor	Code	LPP		HPP	
		Impact	Rank	Impact	Rank
Insufficient period for construction completion[b]	PC	2.067	1	0.647	5
Design accuracy provided by employer[b]	PC	1.615	2	0.235	26
Weather and climate uncertainty	PS	1.429	3	0.824	1
Overall construction method difficulties	CAT	1.429	3	0.667	3
Insufficient time for bid preparation[a]	PC	1.200	5	0.125	34
JV's insufficient construction capability[b]	CAP	1.143	6	0.111	41
Difference in culture, customs, and routines	CI	1.000	7	0.235	3
IT based project management difficulties	CAT	1.000	7	0.667	26
Insufficient project management capability of employer	PO	0.933	9	0.375	14
Unfavorable liquidated damage agreement	PC	0.933	9	0.294	21

[a]Correlation is significance at the 0.1 level (two tailed), [b]Correlation is significance at the 0.05 level (two tailed)

Table 6. shows the probability of top 10 risk factors in building projects. ‘Insufficient period for construction completion’ ranked first in both LPP and HPP, indicating that the frequency of this risk factor was the highest in both LPP and HPP. ‘Weather and climate uncertainty’, ‘IT based project management difficulties’ ranked high in both LPP and HPP. Especially, ‘New construction technology difficulties’ and ‘Informal request by employer’ are the biggest difference in rank between LPP and HPP. These two risk factors must be managed to obtain high return in aspects of cost performance.

Table 6. Probability of top 10 risk factors in building

Risk Factor	Code	LPP		HPP	
		Probability	Rank	Probability	Rank
Insufficient period for construction completion	PC	66.7%	1	64.7%	1
Weather and climate uncertainty	PS	64.3%	2	47.1%	5
JV's insufficient construction capability[a]	CAP	64.3%	2	33.3%	23
Design accuracy provided by employer	PC	61.5%	4	41.2%	14
New construction technology difficulties[a]	CAT	58.3%	5	23.1%	42
IT based project management difficulties	CAT	58.3%	5	44.4%	8
Insufficient specification provided by employer	PC	57.1%	7	29.4%	26
Overall construction method difficulties	CAT	57.1%	7	33.3%	23
Poor infra and logistics condition[a]	CI	53.3%	9	29.4%	26
Informal request by employer[a]	PO	53.3%	9	17.6%	46

[a]Correlation is significance at the 0.1 level (two tailed), [b]Correlation is significance at the 0.05 level (two tailed)

3.3. Plant

Table 7. shows the impact of top 10 risk factors in plant projects. 7 out of 10 risk factors ranked high in both LPP and HPP. It means that impact is not important criterion for distinguishing between LPP and HPP. ‘Uncertainty of local currency’, ‘Unfavorable liquidated damage agreement’ and ‘Unfavorable claim and arbitration agreement’ ranked only high in LPP. Especially ‘Uncertainty of local currency’ has positive impact on cost performance in HPP.

Table 7. Impact of top 10 risk factors in plant

Risk Factor	Code	LPP		HPP	
		Impact	Rank	Impact	Rank
Design accuracy provided by employer	PC	1.071	1	0.625	2
Informal request by employer[a]	PO	1.000	2	0.250	8
Insufficient project management capability of employer	PO	0.786	3	0.250	8
Insufficient specification provided by employer	PC	0.786	3	0.250	8
Political instability such as civil war and regime change	CP	0.625	5	0.875	1
Insufficient period for construction completion	PC	0.563	6	0.500	3
Corruption, collusion, and underground deal practice	CP	0.500	7	0.250	8
Uncertainty of local currency[b]	CE	0.500	7	-0.143	41
Unfavorable liquidated damage agreement[a]	PC	0.467	9	0.000	27
Unfavorable claim and arbitration agreement[a]	PC	0.467	9	0.000	27

[a]Correlation is significance at the 0.1 level (two tailed), [b]Correlation is significance at the 0.05 level (two tailed)

Table 8. shows the probability of top 10 risk factors in plant projects. 6 out of 10 risk factors have a rank difference between LPP and HPP. It means that probability is a relatively important criterion for distinguishing between LPP and HPP than impact. Therefore, practitioner should develop a response plan that mitigates the probability. ‘Design accuracy provided by employer’, ‘IT based project management difficulties’, ‘Insufficient specification provided by employer’ and ‘Overall construction method difficulties’ were ranked high in both LPP and HPP.

Table 8. Probability of top 10 risk factors in plant projects

Risk Factor	Code	LPP		HPP	
		Probability	Rank	Probability	Rank
Design accuracy provided by employer	PC	57.1%	1	62.5%	2
Insufficient period for construction completion[a]	PC	56.3%	2	37.5%	13
IT based project management difficulties	CAT	56.3%	2	50.0%	5
Subcontractor supply difficulties in host country	CI	53.3%	4	37.5%	13
Informal request by employer[a]	PO	53.3%	4	25.0%	29
Administrative approval and licensing delays	PO	50.0%	6	25.0%	29
Insufficient specification provided by employer	PC	50.0%	6	50.0%	5
Overall construction method difficulties	CAT	50.0%	6	67.5%	1
Insufficient time for bid preparation	PC	43.8%	9	28.6%	24
Unrewarded change of law[a]	PC	43.8%	9	12.5%	46

[a]Correlation is significance at the 0.1 level (two tailed), [b]Correlation is significance at the 0.05 level (two tailed)

4. Conclusion

This study aims to derive key risk factors for supporting more accurate risk assessment in practice. To achieve this purpose, this study conducted a structured questionnaire-surveys of 124 international construction projects and collected the cost impact data of 54 risk factors and profitability data. Based on the collected data, projects were classified by cost performance and product type, and comparative analysis was performed from the perspective of impact and probability. The study shows that ‘Insufficient period for construction completion’, ‘Weather and climate uncertainty’ and ‘IT based project management difficulties’ is the high ranked risk factors regardless of project type. ‘Insufficient period for construction completion’ is, especially, the most important risk factor that should be managed in international construction project. In addition, at least 3 out of 10 risk factors are classified as contract risk. Contractors, therefore, need to develop contract risk management capabilities to carry out sustainable business in international markets. Since this study is a pilot study, there is a limitation that it is difficult to provide academical contributions. However, this study is meaningful in that it provides empirical data related to key risk factors, impact, and probability of each factor so that practitioners can more accurately assess risks. In further study, the authors will deal with the risk response strategies to provide more meaningful knowledge for industry and academia.

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References

[1] Lee, K. W., Han, S. H., Park, H., and David Jeong, H, "Empirical analysis of host-country effects in the international construction market: An industry-level approach," Journal of construction engineering and management, vol. 142, issue. 3, 2016, doi:10.1061/(asce)co.1943-7862.0001083 04015092.

[2] Jung, W., Han, S. H., Kim, Y. W., and Choi, J, "Is it true that high risk yields high returns in international construction projects?," 6th International Structural Engineering and Construction Conference: Modern Methods and Advances in Structural Engineering and Construction (ISEC), Jun 2011, pp. 311-316, doi: 10.3850/978-981-08-7920-4-S1-CP16-cd.

[3] Laryea, S., and Hughes, W, "How contractors price risk in bids: theory and practice," Construction management and economics, vol. 26 issue. 9, 2008, pp. 911-924, doi: 10.1080/01446190802317718.

[4] Qazi, A., Quigley, J., Dickson, A., and Kirytopoulos, K, "Project Complexity and Risk Management (ProCRiM): Towards modelling project complexity driven risk paths in construction projects," International journal of project management, vol. 34, issue 7, 2016, pp. 1183-1198, doi:10.1016/j.ijproman.2016.05.008.

[5] Won, J. W., Jung, W., Han, S. H., Yun, S., and Koo, B, "What enables a high-risk project to yield high return from a construction contractor's perspective?," Sustainability, vol. 11, issue. 21, 2019, doi: 10.3390/su11215971

[6] Jung, W., and Han, S. H. "Which risk management is most crucial for controlling project cost?," Journal of Management in Engineering, vol. 33, issue 5, 2017, doi: 10.1061/(ASCE)ME.1943-5479.0000547.

[7] Fay, M. P., and Proschan, M. A. "Wilcoxon-Mann-Whitney or t-test? On assumptions for hypothesis tests and multiple interpretations of decision rules." Statistics surveys, vol. 4, issue 1, 2010, pp. 4-3,. doi: 10.1214/09-SS051

INVESTIGATION OF CONSTRUCTION PRACTICES FOR DIGITAL TERRAIN MODELS (DTMS) AMONG STATE DEPARTMENTS OF TRANSPORTATION

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Abstract

Digital Terrain Models, commonly known as DTMs, is a principal component of 3D models in construction projects. DTMs provide a digital topographic model of the earth's surface, with input from terrestrial and/or aerial surveying technologies. Departments of Transportation (DOTs) in the United States have implemented different practices to use DTMs in their highway and infrastructure construction projects. With the absence of studies tackling practices for construction-ready DTMs, it becomes important to understand and investigate how state DOTs vary in their deployment and implementation of DTMs in construction. To achieve this objective, data gathered from a nationwide survey was first used to cluster state DOTs into three categories based on their DTM experience in construction: beginner, moderate, and advanced. The two metrics used to categorize state DOTs were the total years of using DTM and the number of projects annually that use DTM. Then, nine DTM aspects were analyzed for the three state DOT categories, namely: sources, training, use cases, handover, project sizes, project types, project-specific benefits, long-term benefits, and challenges. Findings from this paper can assist state DOT professionals in (1) assessing their agency’s current level of experience with DTM in construction, and (2) providing them with a reference of what other state DOTs (whether with the same expertise level or higher) are doing so they can advance or “level up” their agency’s experience and further leverage the use of DTM in construction.

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Keywords: digital terrain models; department of transportation; DTMs; DOTs

1. Background

Several recent initiatives have sought to push the use of three-dimensional models (3D models) into highway and infrastructure projects. In 2009, the Federal Highway Administration (FHWA) and the American Association of State Highway and Transportation (AASHTO) began the Every Day Counts (EDC) program to identify and deploy underutilized innovations in construction projects, especially for state Departments of Transportation (DOTs) [1]. Between the six EDC rounds that happened thus far, four have discussed the use of 3D models throughout the different lifecycles of a construction project [2]–[6]. Major benefits of 3D models include improved project delivery, improved communication, enhanced clash detection and identification of errors, improved visualization, and cost savings [7].

A major component of the 3D model is the Digital Terrain Model (DTM). A DTM is a “digital topographic model of the earth's surface that can be manipulated through computer-aided design programs” [8]. DTMs are constructed using data acquired via remote sensing technologies, both aerial or terrestrial, such as LiDAR, 3D laser scanning, and georeferenced point clouds with high-resolution imagery [8], [9]. Because of the importance of DTMs, the National Cooperative Highway Research Program (NCHRP) called for a synthesis project (Synthesis 560) to document and study the processes and strategies used by state DOTs for the use and transfer of DTMs from design to construction of highway projects [10].

The findings of the NCHRP study documented the state of practice of DTMs across all DOTs and reported results broadly, showcasing that not all DOTs share the same level of DTM experience. Thus, a deeper dive into these practices is needed to better understand how the deployment and implementation of DTM in construction vary with the DOT's level of DTM experience. Such analysis can assist state DOT practitioners and researchers in (1) assessing their agency's current level of experience with DTM in construction, and (2) providing a reference of what other state DOTs (whether with the same expertise level or higher) are doing so they can advance or "level up" their agency's experience and further leverage the use of DTM in construction. Therefore, this paper uses the NCHRP data to characterize state DOTs according to their DTM experience in construction into *beginner*, *moderate*, and *advanced* to provide insights into how the DTM practices vary across the three levels.

2. Methodology

A survey was first created on Qualtrics and included questions targeting different DTM areas, namely: sources of DTM, training, use cases, handover, benefits, and challenges. The survey also asked about the number of projects that use DTM annually and the number of years that the DOT has been using DTM – both of which were used to group DOTs under three categories based on their DTM experience: *beginner* experience, *moderate* experience, and *advanced* experience. Statistical analysis was then performed to detect similarities and differences between the three categories and draw insights that can help DOTs with their DTM journey. Due to the qualitative nature of the questions, non-parametric tests including Wilcoxon Rank-Sum Test (to test for significant difference among a group, or between two independent groups), Kruskal-Wallis test (to test for significance among three or more groups), Conover-Iman test (a posthoc test to detect the groups with significant differences if Kruskal-Wallis was significant), and Kendall tau-b test (to detect significant correlations) [11]–[14].

3. Data Collection

The survey was built on Qualtrics and distributed by email to AASHTO Committee on Construction (CoC) members in all 50 state DOTs and D.C. Recipients of the survey request were asked to forward the survey to the individual in the DOT who is most knowledgeable with DTMs. A total of 38 complete replies were compiled, for a 75% response rate (Figure 1). The sample size of 38 is enough to have 95% confidence that the real value of every measured metric is within ±8% of the measured value.

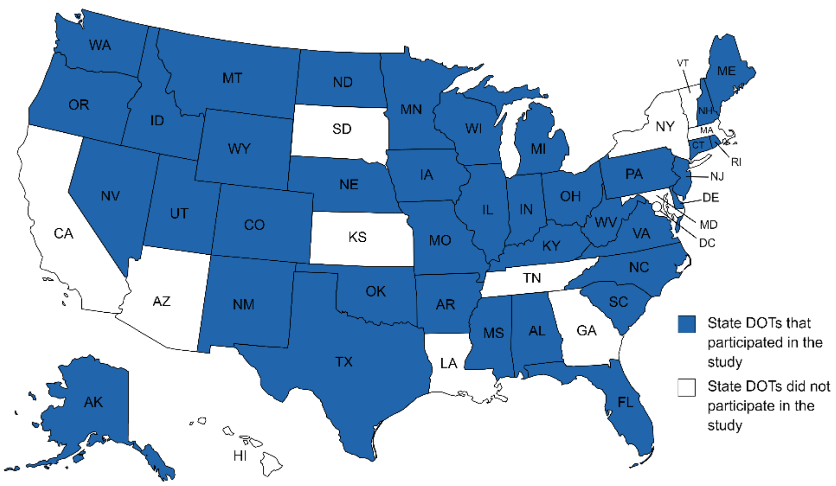

Figure1. A map of state DOTs that participated in the study was generated by MapChart.net (N=38).

Respondents were asked to identify the division in which they work and their corresponding roles. Half of the respondents indicated that they work in the construction division (50%), followed by highway design (18%), CADD/support (18%), then surveying support (8%). The designated roles of respondents varied between construction engineer or engineer manager (48%), followed by CADD/technical supporter (23%), a designer (8%), then a field engineer/inspector (3%). Given the survey was distributed to the AASHTO CoC, this is not a surprising distribution. However, recipients of the survey request were asked to distribute the survey to the individual in the DOT who is most knowledgeable with DTM.

4. Data Analysis and Discussion

As mentioned earlier, DTM practices vary across DOTs, and the perspectives on aspects such as training, use cases, benefits, and challenges could depend on the DOT expertise level of using DTM. Thus, this paper will divide the DOTs into three distinct experience levels depending on the years of using DTM and the number of projects. k-means clustering was employed to group DOTs based on two criteria: (1) the estimated number of years that the DOT has been using DTM in the construction phase and (2) the number of projects that use DTM annually. The clustering analysis yielded three categories as shown in Figure 2:

- **Category 1 – DOTs with Beginner DTM Experience:** This cluster represents 7 DOTs that have been using DTM for less than 10 years on less than 10 projects annually.
- **Category 2 – DOTs with Moderate DTM Experience:** This cluster represents 13 DOTs that have been using DTM for more than 5 years on 10 to 50 projects annually.
- **Category 3 – DOTs with Advanced DTM Experience:** This cluster represents 18 DOTs that have been using DTM for more than 5 years on more than 50 projects annually.

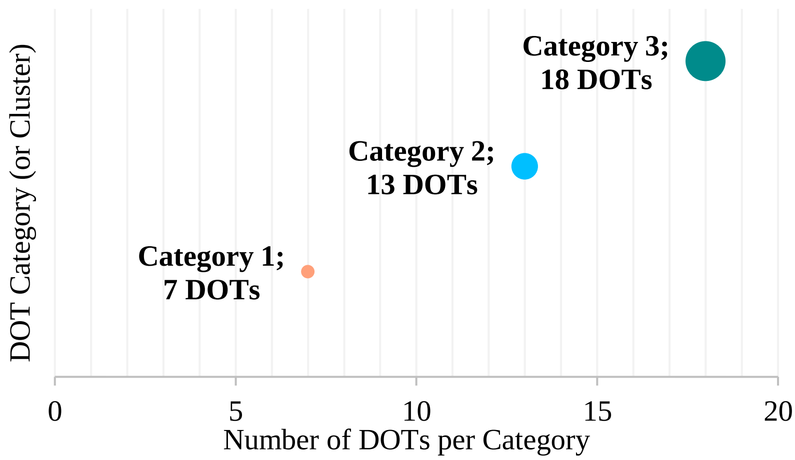

Figure 2. Different DOT categories depend on their level of DTM experience.

4.1. DTM Use Cases

To understand how DOTs, use DTM, the survey provided respondents with a list of 11 use cases and asked them to indicate whether their DOT uses DTM for the specific use case and the frequency of usage on a four-point scale. The scale was converted to a weighted use-case frequency score using Equation (1):

$$Weighted\ UseCase\ Frequency\ Score\ = \frac{\sum_{i=0}^{n}(1r+2s+3o+4a)}{n} \qquad (1)$$

where (n) represents the total number of responses that use DTM for a certain use-case, (r) the number of responses that selected "rarely", (s) represents the number of responses that selected "sometimes", (o) represents the number of responses that selected "often", and (a) represents the number of responses that selected "always". Results are shown in Table 1. Cluster analysis was also performed on the two variables (relative frequency of using the use-case, and the weighted frequency score) to classify use-cases between low usage, middle usage, and high usage for every category. Results are shown in Table 2.

Table 1. Results of Frequency and Weighted Score

	Beginner		Moderate		Advanced	
Use-Case	Relative Frequency*	Weighted Score**	Relative Frequency*	Weighted Score**	Relative Frequency*	Weighted Score**
Automated Machine Guidance	0.71	2.2	0.83	2.5	0.94	2.71
Cost Analysis for Initial Construction Bid	0.43	1.33	0.83	2.1	0.83	2.47
Cost Analysis for Future Maintenance	-	-	0.42	1.2	0.38	1.17
Field Staking	0.71	2	0.92	1.91	0.94	2.69
Grade Work	0.71	2.4	1	2.46	1	3
Pavement Thickness Checks	0.57	1.5	0.42	2	0.82	1.93
Progress Checks	0.71	1.6	0.75	1.89	1	2
QA/QC, Clash Detection, or Reducing Plan Discrepancies	0.43	1	0.85	1.91	0.76	1.85
Quantity Measurements	0.71	2	1	2.25	1	2.24
Survey Verification	0.71	1.6	0.92	2.67	1	2.5
Work Planning, Productivity, or Efficiency	5	6	0.67	1.88	0.56	2

* Relative frequency represents the ratio of the number of respondents that chose the use case within the DTM category to the number of DOTs within the category from Figure 2
** Based on Equation (1)

Starting with DOTs with *beginner* DTM experience (Table 1), most of the DOTs use DTM for “grade work”, “automated machine guidance”, “quantity measurements”, “field staking”, “survey verifications”, and “progress checks”. However, looking at the weighted scores, none of the use cases are on average “often” used among DOTs. Two of the use cases – “cost analysis for future maintenance”, and “work planning, productivity, or efficiency”, were not selected, indicating that DTM is not used by the DOTs.

Table 2. Cluster analysis for use cases.

Use-Case	Beginner	Moderate	Advanced
Automated Machine Guidance	High Usage	High Usage	High Usage
Grade Work	High Usage	High Usage	High Usage
Quantity Measurements	High Usage	High Usage	High Usage
Survey Verification	Middle Usage	High Usage	High Usage
Field Staking	High Usage	Middle Usage	High Usage
Progress Checks	Middle Usage	Middle Usage	High Usage
Cost Analysis for Initial Construction Bid	Low Usage	Middle Usage	High Usage
Pavement Thickness Checks	Low Usage	Middle Usage	Middle Usage
QA/QC, Clash Detection, or Reducing Plan Discrepancies	Low Usage	Middle Usage	Middle Usage
Work Planning, Productivity, or Efficiency	No Usage	Middle Usage	Middle Usage
Cost Analysis for Future Maintenance	No Usage	Low Usage	Low Usage

As for DOTs with *moderate* DTM experience (Table 1), all DOTs use DTM for “grade work” and “quantity measurements”, while less than half use DTM for “pavement thickness checks” and “cost analysis for future maintenance”. Looking at the weighted scores, half the use cases are between “sometimes” and “often”, and the other half is between “rarely” and “sometimes”. Other use cases indicated by this category include “hydraulic design”. Similar results were shown for DOTs with *advanced* DTM experience (Table 1) where all DOTs use “grade work”, “survey verification”, “quantity measurements” and “progress checks” while less than half use DTM for “cost analysis for future maintenance”. Looking at the frequency scores, most of the use cases are between “sometimes” and “often”, with “grade work” being between “often” and “always”. Other use cases indicated by this category include “design”, “PD&E studies”, “visualization”, and “construction sequencing”.

Based on Table 2, it becomes evident that the most common use cases for DTM are “automated machine guidance”, “grade work”, “quantity measurements”, “survey verification”, and “field staking” regardless of their proficiency. On the other hand, DOTs rarely use DTM for “cost analysis for future maintenance”. The number of highly used use cases increases as DOTs become more proficient: DOTs with *advanced* experience have seven use cases that are highly used, while those with *moderate* and beginn*er* have four each. This shows that DOTs with *advanced* experience tested and found wider applicability of DTM for their construction management responsibilities. The results of Table 2 also show that a big room for improvement exists. While DOTs with *beginner* and *moderate* DTM experience can understand how higher categories are utilizing DTM, the use of DTM in the *advanced* category is still not optimized. DOTs of the highest category still have space to further experiment with DTM and use the model for further applications since they already invest in creating it.

4.2. DTM Project Sizes

Respondents were asked to indicate the sizes of the projects that their DOTs use DTM on. Based on Figure 3, the percentage of using DTM regardless of the size of the project increases as DOTs become more proficient with DTM. To understand significant differences between the DOTs, standard error bars to show the confidence intervals of the percentages were compiled and added. The standard error (SE) is used to represent variability in estimates of a parameter and compute a 95% Confidence Interval (CI) that defines a range of values that contains the population parameter as shown in Equation (2):

$$SE = \sqrt{\frac{p(1-p)}{n}} \quad (2)$$

where (p) represents the sample proportion for successes; in this case, it is the percentage that selected the targeted project size and (n) represents the sample size – in this case, the sample size of the DOT group. The general form of the confidence interval is shown in Equation (3):

$$point\ of\ estimate \pm z\alpha_{/2} SE \quad (3)$$

where $point\ of\ estimate$ is the sample proportion p and $(z\alpha_{/2})$ represents the z-score – in this case, from the sample size – in this case, from the standard normal distribution, for a 95% CI and $\alpha = 0.05$, then $z\alpha_{/2} = z_{0.05}/_{2} = 1.96$. Thus, the 95% CI of the percentages is obtained by: $point\ of\ estimate \pm 1.96\ SE$, and the resulting error bars are shown in Figure 3.

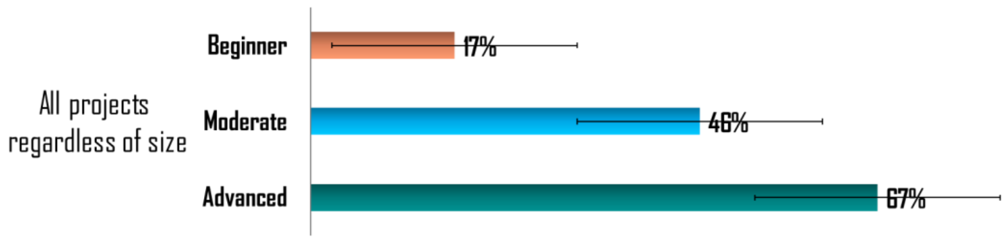

Figure 3. Perspectives of DOTs on the sizes of projects that use DTM.

Based on the standard error bars, while the percentage increase can be significant when comparing *beginner* to *moderate* and *beginner* to *advanced* (because the error bars do not overlap), the same cannot be said about *moderate* and *advanced*. Thus, there is no evidence of a relationship between using DTM for projects regardless of size and the level of DOT experience.

4.3. DTM Project-Specific Benefits

To evaluate the project-based benefits of using DTM on construction projects, the survey asked respondents to evaluate six major project-based benefits on a five-point Likert scale. The scale was converted to a weighted benefit score using Equation (4):

$$Weighted\ Benefit\ Score = \frac{\sum_{i=0}^{n}(1VL+2L+3M+4H+5VH)}{n} \quad (4)$$

where (n) represents the total number of responses that evaluated a certain project-based benefit, (VL) the number of responses that selected “very low”, (L) represents the number of responses that selected “low”, (M) the number of responses that selected “moderate”, (H) represents the number of responses that selected “high”, and (VH) represents the number of responses that selected “very high”.

The results are summarized in Figure 4. Note that the bars shown are for standard deviation, and not standard errors. DOTs with *beginner* and *moderate* DTM experience indicated that “earlier identification of plan discrepancies and conflicts” is the top project-specific benefit, while DOTs with *advanced* experience selected “easier to calculate construction quantities”. On the other hand, DOTs with *moderate* DTM experience considered “fewer change orders” as the least perceived project-specific benefit, while DOTs with *beginner* and *advanced* experience selected “fewer project delays”. In addition to the benefits listed in the figure, DOTs with *advanced* DTM experience identified the “ability to identify areas for excess materials in R/W”, “enhanced survey stakeout and grade control” as a very-high benefit, “staging as very-high project-specific benefits, “improved safety” as a high benefit, and “reduced labor needs” as a moderate benefit. No other benefits were identified from the remaining DOT categories.

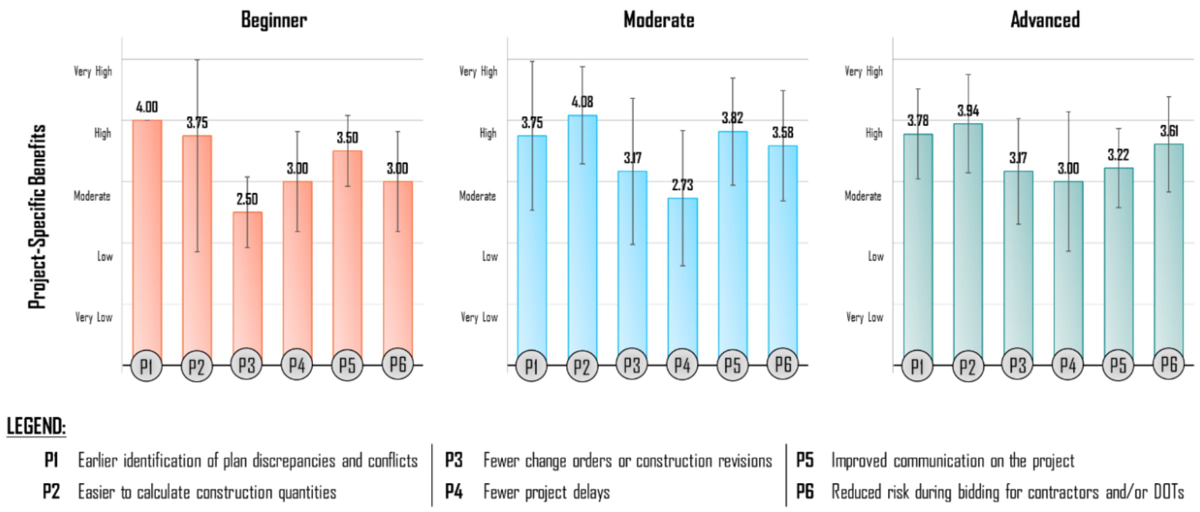

Figure 4. The perspective of DOTs on DTM project-specific benefits.

Three statistical tests were performed. First, Kruskal Wallis tests for any significant difference between the three scores of the DOTs for every project-specific benefit (for example: are there any statistical differences between the scores given by DOTs with beginner, moderate, and advanced for P4?). If significant, the Conover test was performed to detect which pairwise comparisons were significant. Third, a Correlation test was performed to detect correlations between the values and the category of the DOT (for example: are there any positive or negative correlations between the scores of P4 as DOTs became more proficient?). Results are shown in Table 3.

Based on Table 3, none of the tests yielded a significant result, indicating that there is no evidence for significant differences between the three scores on every benefit. Furthermore, no correlations were detected. The results imply that the increase in the proficiency of DOTs does not increase or decrease the score on any of the project-specific benefits. This is not surprising, especially that DOTs that are at the beginning of the DTM journey have anticipated benefits that will mostly end up matching the measured benefits perceived by DOTs with advanced experience. Moreover, with most of the scores lying between “Moderate” and “High” (Figure 4), and none of the scores changing as DOTs become proficient, the maximum capabilities of DTM have yet to be utilized in projects regardless of the DOT category, and the high value of project-specific benefits are yet to be perceived.

Table 3. Results of the statistical tests to detect significant differences and/ or correlations between the scores of the three DOT categories on every project-specific benefit.

	Kruskal-Wallis Test		Kendall Correlation Test	
Project-Specific Benefit	P-value	Status	P-value	Status
P1 Earlier identification of plan discrepancies and conflicts	0.82	Not Significant	0.55	Not Significant
P2 Easier to calculate construction quantities	0.87	Not Significant	0.59	Not Significant
P3 Fewer change orders or construction revisions	0.3	Not Significant	0.28	Not Significant
P4 Fewer project delays	0.69	Not Significant	0.93	Not Significant
P5 Improved communication on the project	0.11	Not Significant	0.10	Not Significant

Based on Table 3, none of the tests yielded a significant result, indicating that there is no evidence for significant differences between the three scores on every benefit. Furthermore, no correlations were detected. The results imply that the increase in the proficiency of DOTs does not increase or decrease the score on any of the project-specific benefits. This is not surprising, especially that DOTs that are at the beginning of the DTM journey have anticipated benefits that will mostly end up matching the measured benefits perceived by DOTs with advanced experience. Moreover, with most of the scores lying between “Moderate” and “High” (Figure 4), and none of the scores changing as DOTs become proficient, the maximum capabilities of DTM have yet to be utilized in projects regardless of the DOT category, and the high value of project-specific benefits are yet to be perceived.

4.4. DTM Long-Term Benefits

The survey also asked respondents to evaluate the long-term benefits of using DTM on construction projects. Like project-specific benefits, the evaluation of the six long-term benefits was on a five-point Likert scale, and the scale was converted to a weighted benefit score using Equation (4). The results are summarized in Figure 5. Note that the bars shown are for standard deviation, not standard errors.

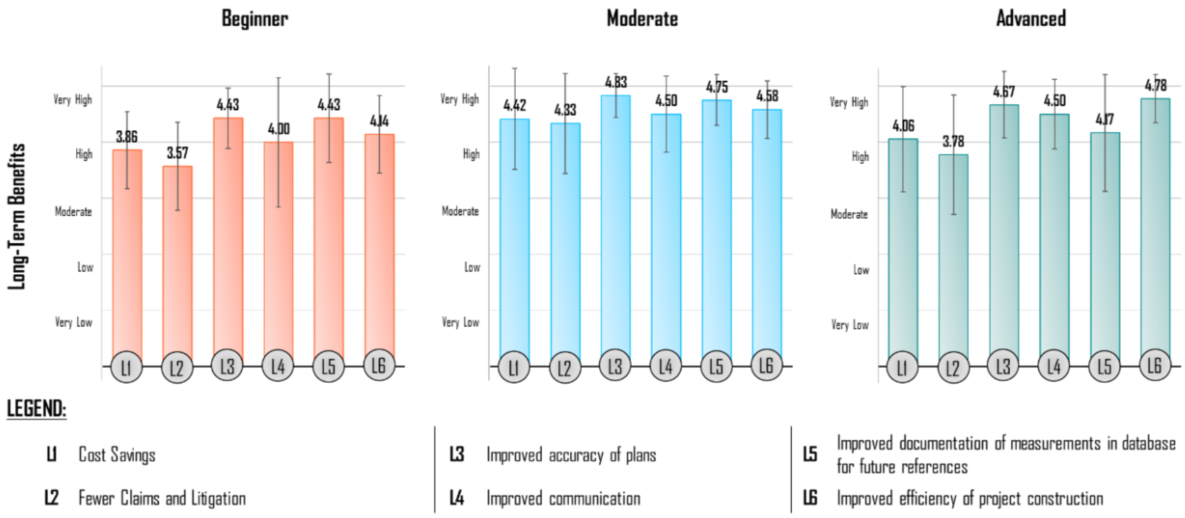

Figure 5. The perspective of DOTs on DTM long-term benefits.

DOTs with *beginner* and *moderate* DTM experience indicated that “improved accuracy of plans” is the top long-term benefit, while DOTs with *advanced* experience selected “improved efficiency of project construction”. On the other hand, all DOTs regardless of DTM experience selected “fewer claims and litigation” as the least perceived long-term benefit. In addition to the benefits listed in the figure, DOTs with *moderate* DTM experience also identified “reduce the need for paper plans” as a moderate long-term benefit, while DOTs with *advanced* DTM experience identified “quicker time to completion” as a high benefit and “improve construction quality” as a very high benefit. The scores provided for long-term benefits seem consistent with project-specific benefits (Figure 4). L3 and L6 scored the highest among DOTs as long-term benefits (Figure 5), similar to P1 and P2 which scored highest as project-based benefits (Figure 4). In contrast, P3 and P4 scores as the lowest among DOTs as project-specific benefits, similar to L2 being the least rated long-term benefit.

The three statistical tests were also performed for the long-term benefits as shown in Table 4: Kruskal Wallis tests for any significant difference between the three scores of the DOTs for every long-term benefit, the Conover test to detect which of the pairwise comparisons were significant (if Kruskal was significant), and Correlation test to detect correlations between the values and the category of the DOT.

Table 4 . Results of the statistical tests to detect significant differences and/ or correlations between the scores of the three DOT categories on every project-specific benefit.

	Kruskal-Wallis Test		Kendall Correlation Test	
Project-Specific Benefit	P-value	Status	P-value	Status
L1 Cost savings	0.22	Not Significant	0.91	Not Significant
L2 Fewer claims and litigation	0.08	Not Significant	0.91	Not Significant
L3 Improved accuracy of plans	0.20	Not Significant	0.46	Not Significant
L4 Improved communication	0.57	Not Significant	0.46	Not Significant
L5 Improved documentation of measurements in the database for future references	0.27	Not Significant	0.31	Not Significant
L6 Improved efficiency of project construction	0.05	Significant*	0.02	Significant* ($\tau_b = 0.365$)

Based on Table 4, the only significant differences were detected for benefit L6. Based on the Conover test, the significant difference was between the score given by DOTs with a *beginner* DTM experience (4.14) and DOTs with *advanced* experience (4.78), where the pairwise comparison yielded a p-value of 0.0074 (significant at 95% confidence). The correlation test also showed significance, where the Kendall coefficient (0.419) shows a positive correlation. This implies that as DOTs become more proficient, their perception of DTM improving project efficiency becomes higher. This finding emphasizes that DTM proficiency increases awareness of the depth of available data within the DTM as compared to traditional plans and cross-sections. As for other long-term benefits, all statistical tests were non-significant. Like project-based benefits, the results imply that the increase in the proficiency of DOTs does not increase or decrease the score on any of the project-specific benefits aside from L6. However, unlike project-specific benefits, most of the scores of the long-term benefits are between "high" and "very high" (Figure 5). This implies that despite DOTs not yet experiencing the full potential of DTM in projects, they are optimistic about the long-term benefits that DTM will bring to construction projects.

4.5. DTM Challenges

Respondents were asked to select the challenges their DOTs face and a relative frequency was calculated for every challenge (i.e. ratio of respondents that selected the challenge to the total number of DOTs per category). To further understand the difference between the three categories, cluster analysis was performed on the challenge results to classify them between low impact, medium impact, and high impact for every category. Results are shown in Table 5.

"Insufficient knowledge or training for inspectors" is the only challenge with a high impact on all DOTs, regardless of DTM experience. Insufficient knowledge or training for field survey staff, office staff, and equipment operators also served as major challenges that impact the use of DTM. Another common challenge is "DTM being incomplete or inconsistent with contract plans". The medium to high impact of this challenge can be related to "fewer project delays" and "fewer change orders" scoring low in the benefits section (Figure 4). On the other hand, compatibility and adequacy of software, hardware, and IT infrastructure do not seem to be hindering the use of DTM. This is especially important for DOTs with *beginner* DTM experience as they try to develop the infrastructure for the technology and implement it across their projects. Another positive aspect is that DOTs seem to agree that the benefits of DTM are known and the ROI is proven regardless of their level of experience with the technology, which in turn reflects on the high scores that the DOTs gave for long-term benefits (Figure 5).

Table 5. Cluster analysis for challenges.

Challenge	Beginner	Moderate	Advanced
Insufficient knowledge or training for inspectors (DOT or CEI)	High Impact	High Impact	High Impact
Insufficient knowledge or training for field survey staff	Medium Impact	High Impact	High Impact
Insufficient knowledge or training for office staff	Medium Impact	High Impact	High Impact
DTM is often incomplete and inconsistent with contract plans	Medium Impact	High Impact	Medium Impact
Insufficient knowledge or training for equipment operators	Medium Impact	Medium Impact	Medium Impact
Designer fear of problems with DTM/lack of confidence	Medium Impact	High Impact	Low Impact
Fear of contractor changing terrain model or introducing error into electronic plan files	Low Impact	High Impact	Low Impact
High cost for owner to stay current with field technology using DTM	Medium Impact	Medium Impact	Low Impact
High cost for the owner for initial software and hardware	Medium Impact	Medium Impact	Low Impact
Incompatibility of existing software	Low Impact	Medium Impact	Low Impact
Inadequacy of Information Technology (IT) Infrastructure	Low Impact	Medium Impact	Low Impact
The benefits are unknown; Return on investment (ROI) is unproven	Low Impact	Medium Impact	Low Impact
Incompatibility of existing hardware	Low Impact	Low Impact	Low Impact

5. Conclusion

The objective of this paper is to understand the different practices that DOTs use with DTMs. The paper utilized data from a nationwide survey to cluster state DOTs into three categories based on their DTM experience in construction: beginner, moderate, and advanced. The two metrics used to categorize state DOTs were the total years of using DTM and the number of projects annually that use DTM. Then, five DTM aspects were analyzed for the three state DOT categories, namely: use cases, project sizes, project-specific benefits, long-term benefits, and challenges. The findings of the paper are limited to the 38 DOTs and the insights of the professionals who filled out the survey. Further studies can elaborate on the perspectives of DOT staff working in other divisions or contractors that work with DOTs, perform a retrospective analysis of DTM usage for cost savings, and follow up on the means proficient DOTs employ to train and support staff on DTM usage.

Acknowledgments

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References

[1] Federal Highway Administration, “Every Day Counts: Innovation for a Nation on the Move,” 2021.
[2] Federal Highway Administration, “EDC-3 Final Report,” Washington, DC. USA, FHWA-17-CAI-005, 2017.
[3] Federal Highway Administration, “EDC-4 Final Report,” Washington, DC. USA, FHWA-19-CAI-013, 2019.
[4] R. Elliot, K. Weinser, and D. Unkefer, “e-Ticketing and Digital As-Builts,” Federal Highway Administration, Washington, DC. USA, FHWA-20-CAI-008, 2021.
[5] D. Unkefer, “About 3D Engineered Models,” *U.S. Department of Transportation Federal Highway Administration*, 2017.
[6] C. Schneider, “3D Engineered Models: Schedule, Cost, and Post-Construction,” Federal Highway Administration, Washington, DC. USA, 2013.
[7] C. Schneider, “3D, 4D, and 5D engineered models for construction,” Federal Highway Administration, Washington, DC. USA, FHWA-HIF-13-048, 2013. [Online].
[8] G. D. Reeder and G. A. Nelson, “Implementation manual—3D engineered models for highway construction: The Iowa experience,” Iowa DOT, Project RB33-014, 2015.
[9] R. Catchings, S. Waddle, H. Nassereddine, G. B. Dadi, M. B. Hatoum, and W. Johnson, “Construction-Ready Digital Terrain Models,” *KY Transportation Center*, KTC-20-06/SPR19-576-1F, 2020, https://doi.org/10.13023/ktc.rr.2020.06.
[10] G. B. Dadi, H. Nassereddine, R. Catchings, M. B. Hatoum, and M. Piskernik, “Practices for Construction-Ready Digital Terrain Models,” *NCHRP Synthesis 560*, 2021, https://doi.org/10.17226/26085.
[11] H. B. Mann and D. R. Whitney, “On a test of whether one of two random variables is stochastically larger than the other,” *Inst. Math. Stat.*, vol. 18, no. 1, pp. 50–60, 1947 http://www.jstor.org/stable/2236101.
[12] W. H. Kruskal and W. A. Wallis, “Use of ranks in one-criterion variance analysis,” *J. Am. Stat. Assoc.*, vol. 47, no. 260, pp. 583–621, 1952, https://doi.org/10.1080/01621459.1952.10483441.
[13] W. J. Conover and R. L. Iman, “On multiple-comparisons procedures,” Los Alamos Scientific Laboratory, Informal Report LA-766-MS, 1979.
[14] M. G. Kendall, “A new measure of rank correlation,” *Biometrika*, vol. 30, no. 1/2, pp. 81–93, 1938.

GREEN BUILDING: AN ANTIDOTE TO SICK BUILDING SYNDROME MENACE IN AFRICA

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Abstract
Sick building syndrome (SBS) is the leading cause of the reduction in the building's occupancy level of satisfaction, poor indoor air quality, and other shenanigans responsible for the underperformance of building occupants and loss in property value. Thus, this study proposed adopting green building (GB) as an antidote for reducing the causes of SBS. The challenges impeding the adoption of GB as an antidote for SBS were also examined in this study. The methodology adopted in this study was broken down into three-phase, with the first phase focused on the data collection. The study adopted a random sampling in collecting data (questionnaire) from construction stakeholders within the study area. A total of one hundred and twenty (120) questionnaires were collected from the respondents within the study area. The questionnaire was analysed using SPSS V 24, adopting frequency distribution, mean score, principal component analysis, and multiple regression analysis. The causes of SBS are divided into the ambience and individual-related factors. The findings from the multiple regression analysis revealed that green building (GB) has a higher chance of functioning as an antidote for eliminating the ambiance-related factors. Unfortunately, factors such as insufficient technical knowledge of green building components, green building occupants' behaviour, and maintenance/construction cost hinder the adoption of GB as an antidote for SBS. This study contributed to creating innovative ways towards eliminating SBS in Africa. The article presented a two-way directional framework that reveals the solution and challenges for adopting green building (GB) as an antidote for sick building syndrome (SBS). Numerous articles have identified the causes of SBS, but there is a shortage in the literature regarding a suitable solution or antidote for eliminating the specific cause of SBS.

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Keywords: Green building, Healthy living, Indoor environmental quality, Sick building syndrome, Sustainable building.

1. Introduction

The relationship between buildings and occupant health has been a significant concern for built environment specialists and health practitioners. In support of the affirmation, [9] affirmed that the connection or association between building occupants and their health condition is the most significant relationship. The relationship became substantial and widespread in the early '90s owing to the rising epidemic caused by overpopulation and a flawed sanitary system in buildings [17]. [3] believed that the health illness suffered by building occupants was the primary driver of the relationship between buildings and their occupants. Thus, it can be implied that individuals can suffer health challenges due to their location in a particular building.

Aside from health challenges, [33] discovered that building inhabitants can also suffer low productivity due to the nature of their building. [24] confirmed that the low productivity of workers is a function of their building. Furthermore, [41] asserted that there is an interaction between health and the built environment. The interaction is responsible for the health discomfort such as respiratory, mental, cardiovascular, and other health challenges confronting building occupants. [14] related the health discomfort facing individuals in their building to symptoms of sick building syndrome (SBS).

[40] describe sick building syndrome as a scenario in which building inhabitants experience poor health and discomfort, with such discomfort dissipating after leaving the building. [7] provided an elaborate opinion of SBS and described it as a group of symptoms ranging from headaches, cold, eyes, nose, and throat soreness suffered by an individual working or living in a building. Thus, it can be implied that the unique phenomenon of SBS is the ability to occur within a building. The uniqueness of SBS has been a bone of contention as it is often regarded as meaning the same thing as building-related diseases. [35] assisted in differentiating the two and comparing sick building syndrome with building-related diseases. [38] and [25] opined that building-related diseases are health challenges transferred from one building occupant to another. In comparison, SBS occurs owing to the defect within the building or maintenance functions of the building.

However, [16] disagreed that the defect within the building is not the only factor responsible for the occurrence of SBS. The author indicated that the accumulation of toxins, volatile organic compounds, or pollutants in the interior environment is also responsible for SBS. [3] argued that symptoms of SBS are typically caused by poor indoor ventilation. [24] opined that inadequate heating, ventilation, and air conditioning systems are some of the significant drivers of SBS. [8] demonstrated a causal link between building moisture and residents' respiratory health. Their findings indicated that various variables could contribute to the health effects of buildings on their residents. Regardless of the factors responsible for SBS [17] affirmed that it is a menace responsible for poor indoor air quality and discomfort to occupants.

Towards curbing the menace of SBS, different strategies and principles has been proposed by numerous scholars. [16] proposed the adoption of regular fumigation of the building and its surroundings. Some scholars like [25] and [23] suggested diverse strategies for combating or alleviating the impact of SBS on building occupants. The process ranges from properly designing ventilation systems, re-modeling of existing buildings, reduction of dampness, and others. Unfortunately, all the strategies have failed to eradicate sick building syndrome symptoms. The failed strategies created a gap in study regarding innovative ideas for reducing SBS symptoms. In eliminating the gap in research and practice, this study proposed adopting green building as an antidote for sick building syndrome in Africa. Green building was proposed after recognising the therapeutic effect of green materials and components [3]. [9] affirmed that green buildings have the potential to support a healthier lifestyle and low carbon emissions. Therefore, this study examines the factors impeding the utilisation of green buildings as an antidote for SBS syndrome. The impact or chances of green building functioning as an antidote for eliminating the causes of SBS was also examined. The study contributes to practice and research by providing a framework for utilising green building as an antidote to alleviating the causes of SBS.

2. Green Building

The development and construction of green buildings have recently attracted numerous researchers and practitioners. However, [24] indicated that Green buildings had existed since the beginning of time when humans first learned how to build. Green buildings have a long history dating back to the caveman period when cave inhabitants used ecologically friendly materials and built their houses to fit the surroundings. Likewise, [32] submitted that green building originated from early construction methods focused on environmentally friendly materials in the nineteenth century. Ever since, green building has experienced tremendous growth as a vital tool to eliminate the negative impact of human activities on the environment [37].

Green building reduces the negative impacts of human activities on the built environment directly and indirectly. It impacts the built environment directly at the individual level by providing optimised indoor environment quality [12]. It indirectly affects the population level by reducing energy use and air pollutants. Unfortunately, most green building studies have only focused on one aspect (pollution level) while neglecting its impact on the indoor environment quality [3]. A few once, like [41], [37], and [13], only focused on green building occupants' satisfaction with indoor environmental quality while neglecting its impact on sick building syndrome. The absence of studies related to the effect of green building in eliminating SBS could be associated with the different challenges affecting green building development, as shown in Table 1.

Table 1. Challenges in the development of green buildings

Source	Challenges of developing green building
Miller et al. (2009) and Sichali and Banda (2017)	Lack of awareness and technical know how.
Steinemann et al. (2017)	Higher cost for sustainable options.
Pioppi et al. (2020)	Insufficient supply of green product and high cost of construction.
Cedeño-Laurent et al. (2018)	Legislative support and government commitment.
Dwaikat and Ali (2016)	Uncooperative attitude of building occupants to green materials
Olubunmi et al. (2016)	Lack of green building evaluation system
Saleh et al. (2020)	Poor data management system
Chegut et al. (2019)	Procurement cost and high design fees
Pioppi et al. (2020)	Difficulty in integrating sustainable materials into occupants' lifestyle
Cedeño-Laurent et al. (2018)	Lack of manufacturers support, population growth and rapid urbanisation.

Table 1 presents the possible challenges affecting the development, construction, and management of green buildings worldwide. Despite the different challenges confronting the development of green buildings, [9] affirmed that green buildings have served as the primary driver of sustainability in the built environment. [37] indicated that ensuring sustainability in the built environment has become paramount owing to the rapid urbanisation and population that lead to extensive use of natural resources contributing to the greenhouse gas emission from new buildings. [32] discovered that green buildings contribute to sustainability by harmonizing indoor environmental quality and reducing greenhouse gas emissions. Also, the literature review revealed that most studies on green building focused on indoor environmental quality while neglecting its impact on eliminating sick building syndrome.

2.1. Sick Building Syndrome (SBS) and Green Building

The term SBS describes a situation in which building occupants are confronted with severe health discomfort related to the time spent in a building [20]. Sick building syndrome (SBS) is a complication affecting building occupants' health and skin. The complication is experienced in the form of headache, fatigue, and irritation in the upper respiratory throat, eyes, and nose [7]. [35] attributed SBS symptoms to individual risk factors like anxiety and stress, smoking, and lack of communication in working in a building. [16] examined the causes of SBS from another perspective and concluded that the COVID-19 outbreak caused it. The scholar believed that during the outbreak, the stay-at-home order increased building occupants leading to increased indoor air pollution due to more indoor activity. Thus, it can be deduced from the review of literatures that SBS is driven by certain crucial factors.

Regardless of the factors responsible for SBS [18] affirmed that there are different skeptics regarding the validity of the diagnosis of sick building syndrome. One of them emanates from the name as some scholars find it confusing because the building inhabitants suffer the symptoms, not the building. Therefore, they believed it should be termed occupants sick building syndrome since the building occupants feel health discomfort. Some other scholars like [33], [14] and [8] opined that the symptoms of SBS are psychological as some of the symptoms might be imagined by the occupants due to fatigue and stress from working. Scholars like [20] and [33] argued against the notion that SBS is a psychological trauma because the symptoms disappear immediately the occupants leave the building.

Table 2. causes and remedial solutions to sick building syndrome

Source	Causes of sick building syndrome	Remedial solutions
Hosseini et al. (2020)	The stay at home order during the COVID-19 pandemic increased SBS as there was over population within the building. The poor indoor air quality was also responsible for SBS.	Use of dis-infectant and encouraging occupants to spend more time outside their building
Joshi (2008)	Poor maintenance of the HVAC unit that in return lead to the growth of legionella organisms.	Maintenance and retrofitting
Ghaffarianhoseini et al. (2018)	There is no specific cause of SBS but it can be related to the design, maintenance and space optimisation within the building	Re-modelling the entire building
Jafari et al. (2015)	The major contributors of SBS were recycling of air in rooms using fan coils, traffic noise, poor lighting and buildings located in a polluted metropolitan area.	Introduction of building sensors to automatically control the indoor air quality.
Runeson-Broberg and Norbäck (2013)	Poor immune system of building occupants, poor air quality and low social support at work.	Create an enabling working environment
Lu et al. (2016)	Frequent exposure of occupants to building components infested with moulds, fungi and mites. Poor ventilation and light illumination into the building.	Re-design of the ventilation system.
Ismaeel et al. (2022)	Monotonous work environment and poor organisation of the workspace	Renovation

Source: author's review of literature

Table 2 presents the different causes and remedial solutions for sick building syndrome. The article was extracted from Scopus and the web of science database. Articles with the highest citation which focused on examining the causes and proposing possible remedial solutions were selected. The analysis from the article revealed that the significant factors responsible or causing sick building syndrome can be classified into individual and ambience-related factors. The individual-related factors can be attributed to the stress and the work condition of building occupants. [14] and [6] discovered that individual-related factors like occupants' history of atopy, genetic disorders, and low work status contribute to the SBS affecting building occupants. In comparison, the ambience-related factor is attributed to the building components and the indoor environmental quality.

Ambience related factors has been the major causes of sick building syndrome [14], [20], [7]. [20] affirmed that ambience related factor usually occurs inform of legionnaire's disease owing to the contamination of cooling towers by legionella organisms. [22] avowed that legionnaire's disease had been the major pollutant of the indoor environmental quality responsible for SBS. Furthermore, [40] discovered that poor air quality, air pollution, air conditioning pollution, and insufficient thermal comfort are the main drivers of ambience related factors of SBS. The risk factors or drivers are pollutants, including particulate matter (PM2.5 and PM10) generated by heating, cooking, and smoking. [26] provided another risk factors:volatile organic compounds like formaldehyde, carbon dioxide, and other air pollutants.

This study proposed the adoption of green building materials as an antidote to the risk factors responsible for the risk factors triggering SBS. This assertion was also submitted by similar studies like [15] and [37] that discovered the susceptibility of green building materials or components to fungi and bacteria growth. Green building components are labeled green based on their ability to minimize chemical emissions, are less toxic, and are recyclable [13]. The use of green building components is becoming popular for in-home users because they can prevent health risks to building occupants and impede fungal growth [41], [11]. Aside from eliminating the fungal and other bacterial growth green building also support cross ventilation which assists in reducing SBS [28] and [34]. Despite the potential of GB in eliminating the causes of SBS there seems to be a gap in literature concerning the proposition of GB as an antidote for SBS.

3. Methodology

This study evaluated the challenges hindering the adoption of green building as an antidote for sick building syndrome in Africa. The impact of green building components on eliminating the ambience and individual related factors was also appraised. A quantitative research methodology was adopted due to its capacity to effectively compare the findings between existing studies and past studies [2]. [10] provided another justification for adopting quantitative research. The scholar indicated that quantitative analysis supports comparing findings to existing theories and facts. Since this study would compare the results with the current theories related to green buildings and SBS this therefore makes quantitative methodology suitable for this study.

The data for the quantitative methodology was collected using a random sampling technique. The respondents were drawn randomly from construction professionals and project managers within Gauteng Province, South Africa. This study picked Gauteng province out of the other eight provinces in the country because the province has a higher number of construction project managers and buildings than other provinces [29]. A questionnaire was used to collect data from the construction project managers and other stakeholders. The questionnaire was broken down into three sections. The first section examines the personal characteristics of the respondents. The second section appraises the challenges of using a green building as an antidote for SBS. At the same time, the third section of the questionnaire focussed on examining the features of green building could potentially eliminate SBS.

The variables used for developing the questionnaire were sourced from the review of extant literature related to the subject matter. One hundred and fifty (150) questionnaires were distributed to the respondents randomly, but only a hundred and twenty (120) were used for the analysis after checking their consistency. The questionnaire was analysed using a statistical package for social science (SPSS V24) and adopted statistical tests like frequency, mean item score, and principal component analysis. Descriptive statistics like frequency and mean item score was used to analyse the questionnaire's first section (respondents' personal information). The respondents' personal information findings revealed that all the respondents are educated, with 47% possessing a BSc or BTech degree as their highest qualification. The remaining proportion of the respondents has either MSc or Ph.D. as their highest degree. Analysis of the personal information showed that all the respondents have an ample working experience in the management and construction of green buildings. Therefore, their response will be crucial to determining the challenges and efficiency of using a green building as an antidote to the prevention of sick building syndrome.

Principal component analysis (PCA) was used in analysing the challenges or factors hindering the adoption of green buildings as an antidote to SBS. According to [19] PCA function as a statistical tool that supports the reduction of dimensions from factors into meaningful components. Also, [5] indicated that PCA is suitable for multifaceted data or factors with numerous components. [12] opined that the challenges affecting the development of green buildings are multifaceted and therefore requires the use of PCA. The PCA was also used to break the factors or challenges hindering the adoption of green building into meaningful components. Before conducting the PCA the reliability of the data was determined using a Cronbach Alpha test. The Cronbach Alpha gave a value of 0.846 which is above the recommended threshold of 0.7 [39]. Whereas multiple regression analysis was used in examining the impact of GB component in eliminating SBS.

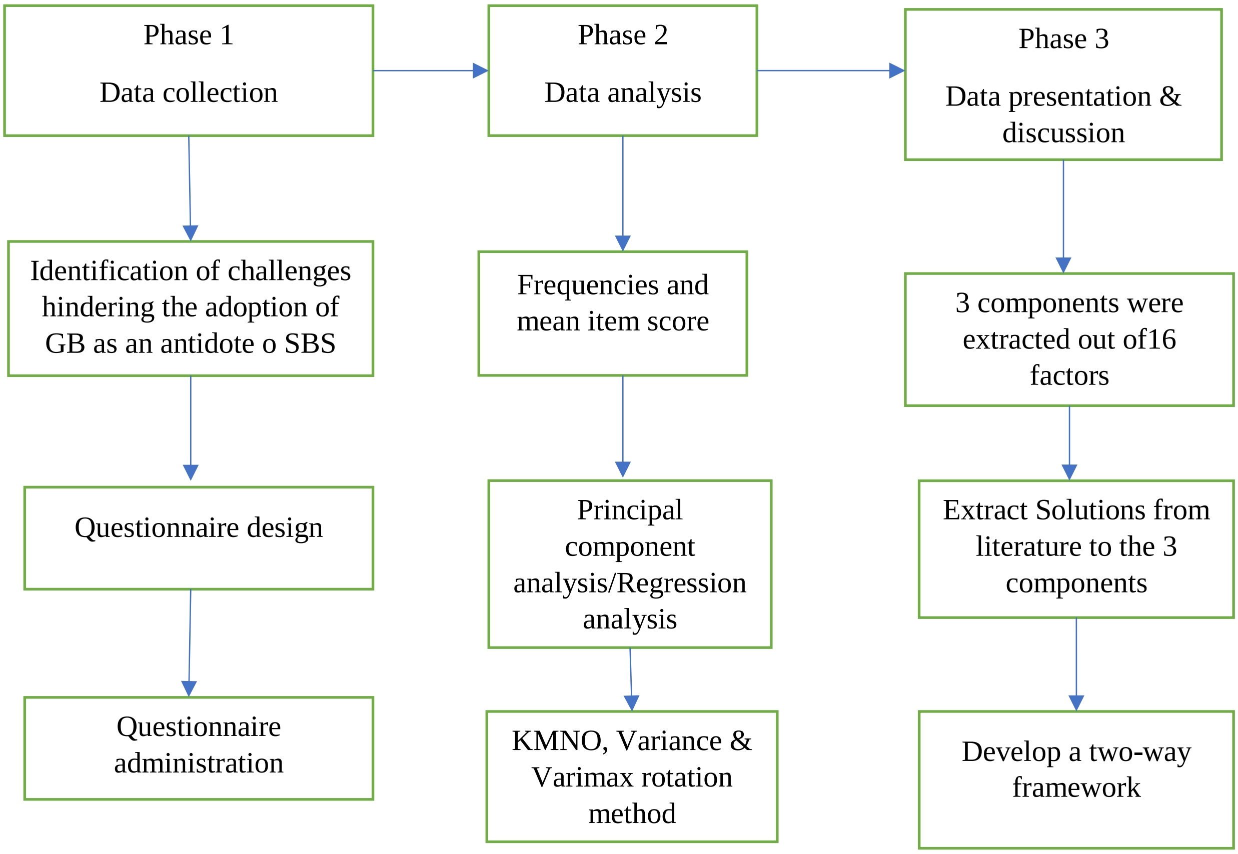

Figure 1: Research methodology framework

Source: author's review of literature

Figure 1 provides a summary of the methodology adopted in this study. The figure showed that the methodology was divided into three phases. Each phase has a minimum of three steps, and the first and second phase (data collection and analysis) have been described extensively in the previous paragraph. Figure 1 revealed that phase 3 (data presentation &discussion) of the research methodology framework is broken down into three steps. The first step involves breaking down the challenges or factors impeding the adoption of GB as an antidote of SBS into meaning dimensions or components. The solutions to the challenges were extracted from the literature, and in-return was, used to develop a two-way directional framework.

4. Discussion of Findings

This section presents the discussion of findings emanating from the analysis of the questionnaire that was distributed to the respondents. The discussion focused on the study's primary objectives: the challenges and impact of green building features in eliminating or reducing sick building syndrome.

4.1. Challenges in adopting green building as an antidote to SBS

The challenges preventing the adoption of green building as an antidote for SBS was analysed in this section. [12] affirmed that the challenges affecting the development of green buildings are multifaceted and therefore require the adoption of multifaceted statistics. This study adopted a principal component analysis (PCA) which is a multifaceted statistic. The challenges hindering green building adoption as an antidote were extracted from literature and then subjected to PCA using SPSS software. The findings from the PCA was broken down into two stages with the first stage used for checking the suitability of the data for PCA. The second stage was used to identify the component preventing the adoption of green buildings as an antidote to SBS.

Table 3. KMNO and Bartlett's test

Kaiser-Meyer-Olkin Measure of Sampling Adequacy		0.748
Bartlett's Test of Sphericity:		
	Approx. Chi-square	1745.364
	Degree of freedom	182
	Significant level	0.000

To determine the suitability (first stage of analysis) of data for principal component analysis, the KMNO and Bartlett's test of sphericity was conducted. The findings from the test were presented by Table 3. The findings from the analysis revealed that the KMNO gave a value of 0.748 which is higher than the recommended threshold of 0.40. According to [19] a KMNO value above 0.40 indicates that the data is suitable for component analysis. The chi-square value in Table 3 gave a significant value (1745.364) at 182 degrees of freedom. It can be confirmed from the KMNO and Bartlett test that the data collected is suitable for principal component analysis.

The second stage entails using the varimax rotation method for grouping the factors that prevent adopting green building as an antidote for SBS into different components. The findings from the varimax rotation revealed that the factors hindering the adoption of green building as an antidote for SBS is made up of three components and are presented in Table 4. The elements in each component, as shown in Table 4 were arranged according to the loadings for each factor.

Table 4. Rotated component matrix

	Component			Variance
	1	2	3	
High cost of green materials	0.843			
Procurement cost	0.829			
Cost of construction	0.800			**37.8%**
Maintenance cost	0.765			
Operating cost	0.674			
Design fees	0.600			
Low technical knowledge		0.760		
Lack of understanding on the therapeutic healing properties of green buildings		0.742		
Lack of investors' interest in green buildings		0.700		
Legislative support from the government		0.672		**15.1%**
Lack of green building maintenance staff		0.628		
Lack of manufacturers' support		0.500		
Occupants' lackadaisical behaviour toward green features			0.862	
The uncooperative attitude of building occupants to green materials			0.840	
Difficulty in integrating sustainable materials into the occupant's lifestyle			0.794	**10.5%**
The unfamiliarity of building occupants to green materials			0.700	

First component: Maintenance and Construction Cost

The first component had six variables; the topmost variables were the high cost of green materials, procurement cost, cost of construction, maintenance cost, and operating cost. All the factors with the component were related and had a variance of 37%. According to [30] and [19], the name given to a component is dependent on the variables within the component. Therefore, this component was called maintenance and construction cost. The component also accounts for a variance of 37.8% in hindering the adoption of green building as an antidote for reducing SBS. [12] also found a similar finding, who affirmed that perceived higher upfront cost accruing to green building construction by building owners and investors hinders its development.

Despite the benefit of green building in boosting the health and productivity of building occupants. [42] discovered that green building maintenance and construction cast a shadow on its benefit. Poor maintenance affects building occupants in the long term because poorly maintained buildings would impact operation cost and its occupants' social and environmental well-being [30]. Towards addressing the maintenance challenges of green buildings [43] made a case for adopting sustainable maintenance for green buildings. The maintenance system that meets the present users' value system without compromising the value system of future users' is known as sustainable maintenance [27]. Therefore, this study proposes the adoption of sustainable maintenance to reduce the maintenance cost attributed to using a green building as an antidote for SBS.

Second component: Low technical knowledge of green building components

The second component gave a variance of 15.1%, which implies that this component is responsible for approximately 15% of problems hindering the adoption of green buildings as an antidote for SBS. The component was listed in Table 4 and shows that the variables have a strong relationship with each other with a variable loading of 0.760 to 0.500. The component comprises of variables like low technical knowledge, lack of understanding on therapeutic healing, lack of investors, and legislative support from the government. The variables within the components were the deciding factor in naming the components. Since the variables within the components focus on the knowledge of green building components, it was called low technical knowledge of green building components. [36] affirmed that poor awareness regarding the therapeutic healing of green building features had prevented its adoption for serving as a healing material. Similarly, [34] discovered that low technical know-how and knowledge regarding green building features had hindered its adoption.

[43] submitted that the performance of a green building is dependent on the component within the structure. Similarly, [17] opined that the relationship between building and health is dependent on the occupant's knowledge of the building components. [3] avowed that occupant's awareness of green building components is often tedious owing to the numerous technologies embedded in green buildings. Towards increasing the knowledge of green building occupants with the components or technologies within the building [21] introduced the concept of beneficiary satisfaction. Although, this concept (beneficiary participation) was first introduced in housing satisfaction studies [1] and [31]. Beneficiary satisfaction allows building occupants involvement with the development and maintenance of building features. This, in return, increases their awareness of the functions of different facilities attached to the green building [21].

Third component: Occupants behaviour

The third component is responsible for 10.5% variance change in the challenges affecting the adoption of green building as an antidote for sick building syndrome. The third component in Table 4 has variables like occupants' lackadaisical behaviour, uncooperative attitude of building occupants to green materials, and difficulty integrating sustainable materials into the occupant's lifestyle. Therefore, this component was called green building occupants' behaviour. A similar study was conducted by [32], who discovered that green building energy efficiency largely depends on the occupant's behaviour.

Occupants' behaviour was described in this study as the attitude or interaction of green building occupants with the building control systems. Similarly, Chen et al (4), in their research, describe occupant behaviour as the visible action or reaction undertaken with the aim of adapting to their environmental conditions. The occupant's response to their environment could be positive or negative depending on their understanding of the environment [4], [21]. To ensure a positive reaction from the building occupants, Laaroussi et al. (2019) [suggested including the building occupant as part of the problem and solution to the problem. Although it might be confusing thus [21] affirmed that occupants' behaviour can be enhanced by creating awareness and incentives for using green building components.

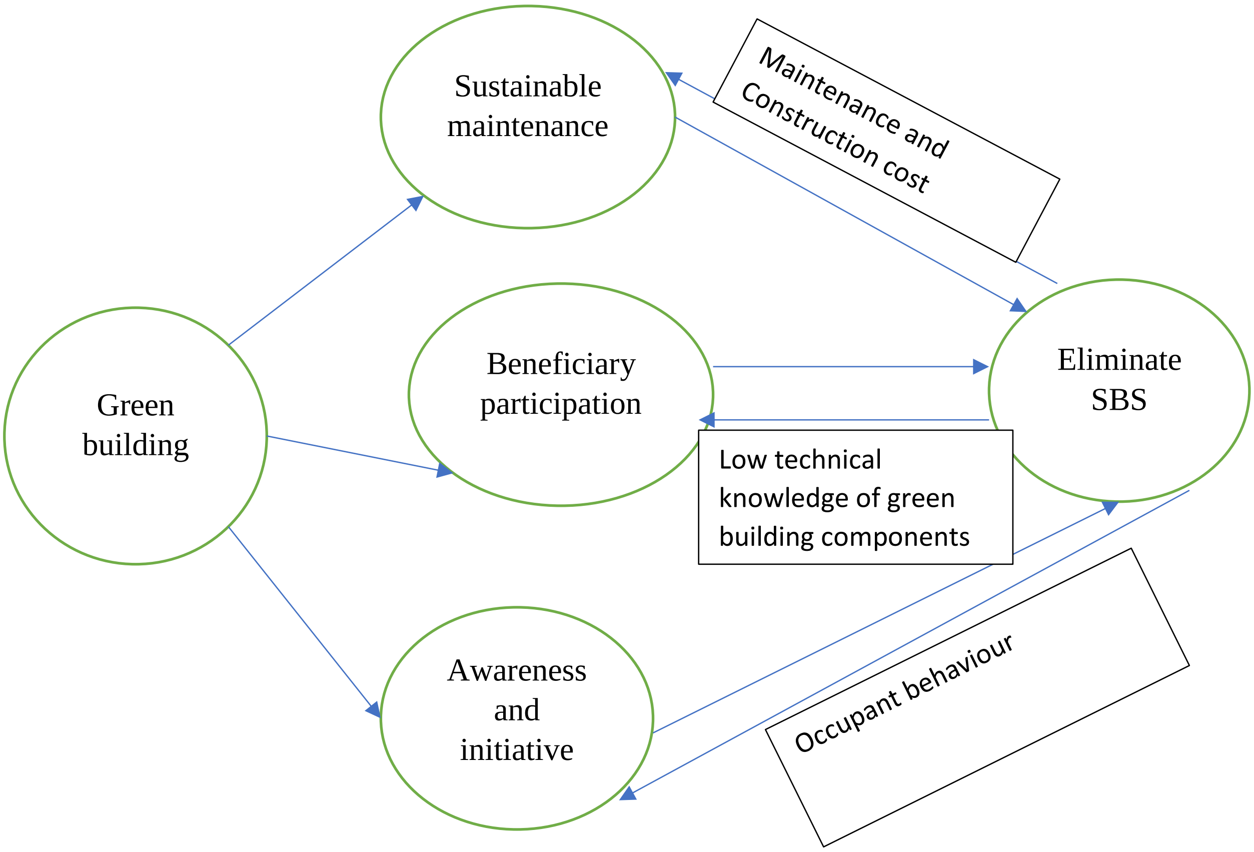

Figure 2: Two-way directional framework for green building as an antidote for SBS

Source: authors review of literature

Figure 2 presents the framework supporting the adoption of green building as an antidote for sick building syndrome (SBS). The framework is divided into two directions called the forward and the backward. This study's objective was to generate the backward (challenges in adopting green building as an antidote to SBS). In comparison, the forward direction provided the solutions to the challenges preventing the adoption of green building as an antidote for SBS. The forward direction was extracted from the review of literatures related to the challenges. Figure 2 revealed that sustainable maintenance, beneficiary participation, and awareness/initiative are the major solutions to adopting green building as an antidote to SBS. It can also be implied that the solutions (forward direction) are the major drivers for adopting green building as an antidote for SBS. Also, the occupant behaviour, low technical knowledge of green building components, and maintenance cost will hinder the adoption of green building as an antidote to SBS.

4.2. Impact of green building materials in eliminating or reducing sick building syndrome

This sub-section presents the impact of green building (GB) materials or components on eliminating the causes of SBS. The impact was determined using multiple regression analysis. The GB components were extracted from literature like [15], [11], and [32] and compressed using a computing function on SPSS into a dummy variable and function as the dependent variable. The causes of SBS were divided into ambience and individual-related factors and used as the independent factor. According to [6] the individual-related factors emanate from building occupant's personal characteristics like their work condition and stress. In comparison, the ambience-related factors are the risk or factors that pollute the indoor environmental quality [26].

Table 5. Multiple regression analysis as an antidote for reducing the causes of SBS

	B	Std.Error	t	Sig	R
Constant	.731	.216	3.384	.000	
Ambience related factor	.561	.157	4.573	.000	**0.628**
Individual related factors	.497	.237	2.097	.004	

Table 5 presents the output from the multiple regression analysis, revealing a significant effect of the green building component in reducing the causes of SBS (ambience and individual-related factors). The t-test gave a positive value for both the ambience and related factors but the ambience factors gave a higher t-test score. This implies that green building has a higher impact on reducing ambience-related factors. Likewise, [11] and [6] opined that optimising the indoor environmental quality through green labelled material can eliminate the risk factors responsible for SBS. [9] Also confirmed that optimisation of the indoor environmental air quality is vital in reducing SBS. The low impact of the GB component on individual-related factors could be attributed to the subjective nature of individual-related factors. Likewise, [33], and [8] opined that the occupants might imagine the individual-related symptoms due to fatigue and stress from working within the building. The value of R greater than 0.4 further confirms that the green building components has the potential for reducing the ambience and individual related factors.

5. Conclusion and Recommendation

The world health organizations, researchers, and industry practitioners have provided numerous opinions or definitions regarding sick-building syndrome (SBS) since the early 80s. It is commonly defined as a malady affecting the proportion of people within a building. It is also regarded as a global health menace to the health and well-being of building occupants. SBS symptoms, including but not limited to headache, fatigue and irritation in the upper respiratory throat, eyes, and nose, have been extensively researched in literature. The symptoms have been attributed to individual risk factors like anxiety and stress, smoking, and lack of communication in working in a building. Although, the findings from modern literature revealed that the stay-at-home order issued by the Government during the COVID-19 pandemic further increased the SBS. The order increases the number of occupants within the building, leading to an increase in indoor air pollution due to more indoor activity.

Sick building syndrome thrives within a building with poor indoor environmental quality; therefore, finding a lasting solution to the causes of SBS in the post-COVID-19 world became paramount. Evidence from literature revealed that SBS is the leading cause of the reduction in the building's occupancy level of satisfaction, poor indoor air quality, and other vices responsible for the underperformance of building occupants and loss in property value. To alleviate the impact of SBS, different strategies have been suggested by researchers and practitioners, ranging from the proper design of ventilation systems, re-modelling of existing buildings, reduction of dampness and others. Unfortunately, all the strategies have failed to eradicate the causes or symptoms of sick building syndrome. The failed strategies created a gap in study regarding innovative ideas in reducing SBS symptoms. To fill the gap, this study proposed adopting green building as an antidote for reducing the symptoms and causes of SBS.

The findings from the literature revealed that the causes of SBS are divided into individual and ambience-related factors. The individual-related factors are causes that are personal or related to the living or working conditions. Thus, the individual related factors include occupants' history of atopy, genetic disorders, and working/living conditions. The individual related factors vary from individual to individual. It was discovered that the individual-related factor is subjective, and thus building occupants may experience different symptoms. The subjective nature of the individual-related factor is responsible for the difficulty in finding a permanent solution to SBS. In contrast, the ambience-related factor is attributed to the building components and indoor environmental quality. The majority of the symptoms of SBS originate from the ambience-related factors which are difficult to eliminate permanently.

This study assisted in redefining the ideas for eliminating the cause and triggering factors responsible for SBS through introducing green building components into conventional buildings. Green building component has been known for their therapeutic healing effects on building occupants. Thus, this study proposed adopting green building as an antidote to eliminate the causes of sick building syndrome. This was proposed after discovering that green building can potentially reduce the negative impacts of human activities on the built environment directly and indirectly. It impacts the built environment directly at the individual level by providing optimised indoor environment quality. The regression analysis findings discovered a significant impact of green building component in serving as an antidote for alleviating the causes of SBS. The antidote will effectively eliminate the ambience-related factor more than the individual related factors.

Despite the efficiency of green building in eliminating the causes of SBS, the application is hindered by low technical knowledge of green building components, green building occupants' behaviour and maintenance and construction cost. This study contributed to creating innovative ways to curb SBS in Africa. The study recommended that awareness be created regarding green buildings' benefit and therapeutic healing potential. The study also recommended that facility managers or construction managers should involve building occupants in designing and installing green building components. The study contributes to research by providing a framework for utilising green building as an antidote to ameliorate the causes of SBS. The study contributes to practice, especially among green building investors, by providing factors that can hinder the adoption of green building developments. An area of further study can be conducted on validating the framework that was developed in this study.

6. References

[1] C. Aigbavboa and W. Thwala, “Prediction of Residential Satisfaction in South African Low-Income Housing: Role of Beneficiaries,” Journal of Architectural Engineering, vol. 24, no. 1, Mar. 2018, doi: 10.1061/(asce)ae.1943-5568.0000282.

[2} C. Aigbavboa and W. Thwala, “Housing development in South Africa,” Residential Satisfaction and Housing Policy Evolution, pp. 109–148, Jul. 2018, doi: 10.1201/9781351012676-9.

[3] Ajayi, O. and Osunsanmi, T. (2018), "Constraints and challenges in the implementation of total quality management (TQM) in contracting organisations", Journal of Construction Project Management and Innovation, Vol. 8 No. 1, pp. 1753-1766.

[4] J. G. Allen, P. MacNaughton, J. G. C. Laurent, S. S. Flanigan, E. S. Eitland, and J. D. Spengler, “Green Buildings and Health,” Current Environmental Health Reports, vol. 2, no. 3, pp. 250–258, Jul. 2015, doi: 10.1007/s40572-015-0063-y.

[5] B. F. Balvedi, E. Ghisi, and R. Lamberts, “A review of occupant behaviour in residential buildings,” Energy and Buildings, vol. 174, pp. 495–505, Sep. 2018, doi: 10.1016/j.enbuild.2018.06.049.

[6] J. R. Beattie and F. W. L. Esmonde-White, “Exploration of Principal Component Analysis: Deriving Principal Component Analysis Visually Using Spectra,” Applied Spectroscopy, vol. 75, no. 4, pp. 361–375, Jan. 2021, doi: 10.1177/0003702820987847.

[7] H. Belachew et al., “Sick building syndrome and associated risk factors among the population of Gondar town, northwest Ethiopia,” Environmental Health and Preventive Medicine, vol. 23, no. 1, Oct. 2018, doi: 10.1186/s12199-018-0745-9.

[8] P. S. Burge, “Sick building syndrome,” Occupational and Environmental Medicine, vol. 61, no. 2, pp. 185–190, Feb. 2004, doi: 10.1136/oem.2003.008813.

[9] J. Cai et al., “Associations of household dampness with asthma, allergies, and airway diseases among preschoolers in two cross-sectional studies in Chongqing, China: Repeated surveys in 2010 and 2019,” Environment International, vol. 140, p. 105752, Jul. 2020, doi: 10.1016/j.envint.2020.105752.

[10] J. G. Cedeño-Laurent et al., “Building Evidence for Health: Green Buildings, Current Science, and Future Challenges,” Annual Review of Public Health, vol. 39, no. 1, pp. 291–308, Apr. 2018, doi: 10.1146/annurev-publhealth-031816-044420.

[11] J. W. Creswell, W. E. Hanson, V. L. Clark Plano, and A. Morales, “Qualitative Research Designs,” The Counseling Psychologist, vol. 35, no. 2, pp. 236–264, Mar. 2007, doi: 10.1177/0011000006287390.

[12] P. De Luca, I. Carbone, and J. B. Nagy, “GREEN BUILDING MATERIALS: A REVIEW OF STATE OF THE ART STUDIES OF INNOVATIVE MATERIALS,” Journal of Green Building, vol. 12, no. 4, pp. 141–161, Nov. 2017, doi: 10.3992/1943-4618.12.4.141.7

[13] L. N. Dwaikat and K. N. Ali, “Green buildings cost premium: A review of empirical evidence,” Energy and Buildings, vol. 110, pp. 396–403, Jan. 2016, doi: 10.1016/j.enbuild.2015.11.021.

[14] G Y. Geng, W. Ji, Z. Wang, B. Lin, and Y. Zhu, “A review of operating performance in green buildings: Energy use, indoor environmental quality and occupant satisfaction,” Energy and Buildings, vol. 183, pp. 500–514, Jan. 2019, doi: 10.1016/j.enbuild.2018.11.017.

[15] A. Ghaffarianhoseini et al., “Sick building syndrome: are we doing enough?,” Architectural Science Review, vol. 61, no. 3, pp. 99–121, May 2018, doi: 10.1080/00038628.2018.1461060.

[16] C. P. Hoang, K. A. Kinney, R. L. Corsi, and P. J. Szaniszlo, “Resistance of green building materials to fungal growth,” International Biodeterioration & Biodegradation, vol. 64, no. 2, pp. 104–113, Mar. 2010, doi: 10.1016/j.ibiod.2009.11.001.

[17] M. R. Hosseini, R. Fouladi-Fard, and R. Aali, “COVID-19 pandemic and sick building syndrome,” Indoor and Built Environment, vol. 29, no. 8, pp. 1181–1183, Jun. 2020, doi: 10.1177/1420326x20935644.

[18] J. Ige et al., “The relationship between buildings and health: a systematic review,” Journal of Public Health, vol. 41, no. 2, pp. e121–e132, Aug. 2018, doi: 10.1093/pubmed/fdy138.

[19] A. Khajevandi, M. Jafari, F. Karamali, and F. Zabeti, “Indoor carbon dioxide concentrations and sick building syndrome symptoms in office workers of petroleum industry health organization,” International Archives of Health Sciences, vol. 5, no. 3, p. 82, 2018, doi: 10.4103/iahs.iahs_27_18.

[20] I. T. Jolliffe and J. Cadima, “Principal component analysis: a review and recent developments,” Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, vol. 374, no. 2065, p. 20150202, Apr. 2016, doi: 10.1098/rsta.2015.0202.

[21] S. Joshi, “The sick building syndrome,” Indian Journal of Occupational and Environmental Medicine, vol. 12, no. 2, p. 61, 2008, doi: 10.4103/0019-5278.43262.

[22] H. G. Kim and S. S. Kim, “Occupants’ Awareness of and Satisfaction with Green Building Technologies in a Certified Office Building,” Sustainability, vol. 12, no. 5, p. 2109, Mar. 2020, doi: 10.3390/su12052109.

[23] P. Kumar, Mohd. A. Kausar, A. B. Singh, and R. Singh, “Biological contaminants in the indoor air environment and their impacts on human health,” Air Quality, Atmosphere & Health, vol. 14, no. 11, pp. 1723–1736, Aug. 2021, doi: 10.1007/s11869-021-00978-z.

[24] S. Mentese et al., “A long-term multi-parametric monitoring study: Indoor air quality (IAQ) and the sources of the pollutants, prevalence of sick building syndrome (SBS) symptoms, and respiratory health indicators,” Atmospheric Pollution Research, vol. 11, no. 12, pp. 2270–2281, Dec. 2020, doi: 10.1016/j.apr.2020.07.016.

[25] N. Miller, D. Pogue, Q. Gough, and S. Davis, “Green Buildings and Productivity,” Journal of Sustainable Real Estate, vol. 1, no. 1, pp. 65–89, Jan. 2009, doi: 10.1080/10835547.2009.12091783.

[26] P. K. Nag, “Sick Building Syndrome and Other Building-Related Illnesses,” Office Buildings, pp. 53–103, Dec. 2018, doi: 10.1007/978-981-13-2577-9_3.

[27] Y. Nakayama et al., “Prevalence and risk factors of pre-sick building syndrome: characteristics of indoor environmental and individual factors,” Environmental Health and Preventive Medicine, vol. 24, no. 1, Dec. 2019, doi: 10.1186/s12199-019-0830-8.

[28] B. F. Ogunbayo, C. O. Aigbavboa, W. Thwala, O. Akinradewo, M. Ikuabe, and S. A. Adekunle, “Review of Culture in Maintenance Management of Public Buildings in Developing Countries,” Buildings, vol. 12, no. 5, p. 677, May 2022, doi: 10.3390/buildings12050677.

[29] O. A. Olubunmi, P. B. Xia, and M. Skitmore, “Green building incentives: A review,” Renewable and Sustainable Energy Reviews, vol. 59, pp. 1611–1621, Jun. 2016, doi: 10.1016/j.rser.2016.01.028.

[30] T. Osunsanmi, C. Aigbavboa, A. Oke, and I. Ohiomah, “Construction 4.0: Its impact towards delivering quality and sustainable houses in South Africa,” Creative Construction Conference 2018 - Proceedings, 2018, doi: 10.3311/ccc2018-020.

[31] T. O. Osunsanmi, C. O. Aigbavboa, A. Oke, and M. E. Onyia, “Making a case for smart buildings in preventing corona-virus: focus on maintenance management challenges,” International Journal of Construction Management, vol. 22, no. 16, pp. 3109–3118, Nov. 2020, doi: 10.1080/15623599.2020.1842960.

[32] T. O. Osunsanmi, C. O. Aigbavboa, W. D. Thwala, and A. E. Oke, “General Introduction,” Construction Supply Chain Management in the Fourth Industrial Revolution Era, pp. 3–15, Sep. 2022, doi: 10.1108/978-1-80382-159-720221001.

[33] B. Pioppi, C. Piselli, C. Crisanti, and A. L. Pisello, “Human-centric green building design: the energy saving potential of occupants’ behaviour enhancement in the office environment,” Journal of Building Performance Simulation, vol. 13, no. 6, pp. 621–644, Sep. 2020, doi: 10.1080/19401493.2020.1810321.

[34] R. Runeson-Broberg and D. Norbäck, “Sick building syndrome (SBS) and sick house syndrome (SHS) in relation to psychosocial stress at work in the Swedish workforce,” International Archives of Occupational and Environmental Health, vol. 86, no. 8, pp. 915–922, Nov. 2012, doi: 10.1007/s00420-012-0827-8.

[35] R. M. Saleh, M. M. Anuar, A. K. A. Swidi, and K. Omar, “The effect of awareness, knowledge and cost on intention to adopt green building practices,” International Journal of Environment and Sustainable Development, vol. 19, no. 1, p. 33, 2020, doi: 10.1504/ijesd.2020.105468.

[36] M. Sarkhosh et al., “Indoor Air Quality associations with sick building syndrome: An application of decision tree technology,” Building and Environment, vol. 188, p. 107446, Jan. 2021, doi: 10.1016/j.buildenv.2020.107446.

[37] M. Sichali and L. J. Banda, “Awareness, Attitudes and Perception of Green Building Practices and Principles in the Zambian Construction Industry: A Qualitative Descriptive Cross Sectional Study,” New Approaches in Engineering Research Vol. 7, pp. 49–58, Jul. 2021, doi: 10.9734/bpi/naer/v7/3092f.

[38] A. Steinemann, P. Wargocki, and B. Rismanchi, “Ten questions concerning green buildings and indoor air quality,” Building and Environment, vol. 112, pp. 351–358, Feb. 2017, doi: 10.1016/j.buildenv.2016.11.010

[39] Y. Sun, J. Hou, R. Cheng, Y. Sheng, X. Zhang, and J. Sundell, “Indoor air quality, ventilation and their associations with sick building syndrome in Chinese homes,” Energy and Buildings, vol. 197, pp. 112–119, Aug. 2019, doi: 10.1016/j.enbuild.2019.05.046.

[40] Tavakol, M. and Dennick, R. (2011), "Making sense of Cronbach's alpha", International journal of medical education, Vol. 2, p. 53 https://doi.org/10.5116/ijme.4dfb.8dfd

[41] M. Wang, L. Li, C. Hou, X. Guo, and H. Fu, “Building and Health: Mapping the Knowledge Development of Sick Building Syndrome,” Buildings, vol. 12, no. 3, p. 287, Mar. 2022, doi: 10.3390/buildings12030287.

[42] W. Wei, O. Ramalho, and C. Mandin, “Indoor air quality requirements in green building certifications,” Building and Environment, vol. 92, pp. 10–19, Oct. 2015, doi: 10.1016/j.buildenv.2015.03.035.

[43] N. N. Zainol et al., “Critical Factors that Lead to Green Building Operations and Maintenance Problems in Malaysia: A Preliminary Study,” Advanced Materials Research, vol. 935, pp. 23–26, May 2014, doi: 10.4028/www.scientific.net/amr.935.23.

[44] J. Zhao, C. Gao, and T. Tang, “A Review of Sustainable Maintenance Strategies for Single Component and Multicomponent Equipment,” Sustainability, vol. 14, no. 5, p. 2992, Mar. 2022, doi: 10.3390/su14052992.

URBAN ENERGY RECYCLING: AN ARCHITECTURAL ROAD MAP

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Abstract

There is a strong link between energy recycling and urbanism. Cities are major energy consumers, and as the world's population continues to urbanise, the demand for energy in cities will only increase. At the same time, cities also generate significant waste and unused energy. Energy recycling can help address both of these issues by capturing and converting this waste and new energy into valuable energy that can be used to power homes, businesses, and other infrastructure within the city. Energy recycling has the potential to play a critical role in the development of sustainable and energy-efficient cities. Urban areas can become more self-sufficient, resilient, and environmentally friendly by capturing and converting waste and unused energy into valuable energy. The paper aims to analyse energy recycling procedures in cities. The research analyses the possibilities of reducing waste, greenhouse gas emissions, energy security and increased energy efficiency. The result of the paper assesses a road map for urban energy recycling in an Architectural and Urban context.

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Keywords: Architectural Designing, Emerging technologies, Energy Recycling, Sustainable infrastructure, Sustainability challenges, System control.

1. Introduction

Energy recycling and urbanisation are closely linked. Cities are the primary energy consumers, and their demands constantly increase. At the same time, cities produce a large amount of waste and unused energy. Energy recycling can help address both problems by capturing and converting waste and new energy into valuable energy to power homes, businesses, and other city infrastructure. Energy recycling converts waste or wasted energy into usable energy for other purposes. This process can take many forms, including the recovery of heat, electricity, or other forms of energy[1].

The current implementation of energy recycling in cities focuses on implementing innovative sustainability strategies. The search for advanced technologies to capture and recycle waste energy from various sources in urban areas is one of the most important contemporary approaches. The search for natural, possibly efficient energy sources is also taking place in the context of using natural resources in the city. Even though cities are most often located in areas not exposed to constant strong winds, urban ventilation of cities on an urban scale is being used. The well-known examples of urban parks or green wedges are designed to ventilate exhaust-filled city centres [2]. Modern research indicates that it is possible to take advantage of winds and solar energy occurring through existing buildings, which is very often seen in the installation of various types of wind turbines or PV panels on the facades of buildings or roofs. The search for new solutions to be applied to urban tissues challenges contemporary technological thought related to sustainable development, especially in applications in specific urban settings. The following article presents current energy generation methods from potential human activity in large cities and provides a road map for designing and retrofitting urban areas.

2. Chosen energy recycling background

2.1. Bio-pharms

Biofarms, which produce energy from plants, is a technology called biomass and involves converting organic material (such as wood, grass, straw, agricultural waste, etc.) into biofuel, which can then be used to produce electricity or heat. The process of producing biofuel from plants at bio-pharms usually involves, among other things, harvesting the raw material, shredding it, drying it, and then fermenting or burning it to produce energy. Biomass can also be used in cogeneration, generating electricity and heat. Biofarms that make energy from plants are becoming increasingly popular, especially in countries with a developed agricultural sector and high energy demand. Bioenergy from plants can be a green and sustainable energy source but requires proper management of production processes to ensure minimal environmental impact and sustainability.

Algae are one of the fastest-growing and most versatile types of biomass because they are easy to grow and have a concise life cycle. Algae can be grown in various places, such as swimming pools, reservoirs, retention tanks and even in closed indoor systems. Many different species of algae have different uses. Some are rich in protein and used in food, others aim to produce biofuels, and others are used in cosmetics and dietary supplements. Algae also benefit the environment, as they consume carbon dioxide and other pollutants from water during photosynthesis. Algae bio-pharms are increasingly popular as a sustainable source of biomass that can replace traditional sources of energy and raw materials, such as oil and coal. Designers are trying to use the idea in their projects. Upi-2m studio has placed biomass-producing towers at the sites of existing gas stations in cities. The studio's research led to the selection of algae and bamboo as giving the best production results (maximum amount of biofuel per unit area/spatial unit), taking into account other factors as well, such as the cost of the technology needed for cultivation and processing, growth rate, annual input-output ratio, etc. In addition, bio-pharms make production independent of most weather events. The studio presented a tower project in Croatia called Biooctanic.

2.2. Waste energy

Another way in which energy recycling is linked to urbanism is through the management of waste. Cities generate much waste sent to landfills or incinerated[3]. By implementing energy recycling technologies, cities can recover energy from this waste, reducing the amount of waste that must be sent to landfills and reducing greenhouse gas emissions. In addition, cities can use this recovered energy to power homes, businesses, and other infrastructure, helping to reduce their reliance on fossil fuels.

Buildings in urban areas generate a significant amount of waste heat that can be captured and reused by district heating and cooling systems[4]. This approach has been successfully implemented in cities such as Copenhagen, Denmark, where waste heat from industrial processes and power plants is used to heat residential buildings and offices.

Another energy recycling strategy is using waste-to-energy plants, which convert municipal solid waste into electricity and heat. This approach has been adopted by several cities worldwide, including Oslo, Norway, where a new waste-to-energy plant is under construction that will provide electricity and heat to some 40,000 households.

2.3. Wind energy

The possibilities of using wind energy in non-urbanised areas and the centre of cities are being analysed. Wind energy is used in cities mainly by installing wind turbines and wind generators on or near the roofs of buildings[5]. They can generate electricity used in buildings or transmitted to the power grid[6]. An example of such a building is the Bahrain World Trade Center, which consists of two towers connected by a bridge. On top of the towers are three wind turbines, each with a diameter of 29 meters, which can provide about 11-15% of the building's demand energy. Another example is Logan Airport in Boston, which is powered by wind turbines installed on the roof of the building.

In recent years, many buildings worldwide are beginning to use wind power to meet their energy needs, and developments in wind power generation technology have helped increase this form of energy in buildings[7]. Wind energy can already be used to power streetlamps and other devices, such as cell phone chargers and weather stations. Still, no such system has yet been invented to generate enough energy for building needs.

2.4. Solar energy

Solar energy recycling is becoming increasingly important in cities as more and more buildings are equipped with solar panels to generate electricity. While solar panels are a great source of renewable energy, they can also produce excess energy that is not used and can potentially go to waste. This is where solar energy recycling comes in - it allows the extra energy to be stored and repurposed for later use.

Recent developments in solar energy recycling include advanced storage technologies such as batteries, which can store excess solar energy generated during the day for use at night or during periods of low sunlight. This ensures that the solar power generated is fully utilised and not wasted. In addition, new software and monitoring systems are being developed to predict energy demand and optimise stored solar energy, further improving efficiency and reducing waste.

Another recent development in solar energy recycling is the use of microgrids. Microgrids are small-scale, localised power grids that can operate independently or in conjunction with the primary power grid[8]. They can store and distribute excess solar energy generated by individual buildings, allowing for more efficient and reliable energy use within a community. This can also reduce the strain on the primary power grid during periods of high demand, improving overall energy reliability and resilience.

3. Energy recycling in practice

To achieve environment-friendly development, it is essential to strengthening the protection of the natural environment in urban construction. The planning and design of an eco-city should be based on the local natural conditions and make a reasonable plan that does not harm the original environment. Environmental quality has a significant impact on human survival and development, and people usually evaluate it from the aspects of physiological and psychological needs. The departments concerned should minimise energy and material consumption, implement renewable energy recycling policies, reduce non-renewable energy use, and maintain the ecological environment while formulating eco-city planning. It is also possible to support enterprises that actively respond to energy conservation and emission reduction and advocate zero pollution to assist the ecological city in moving towards a healthy path. Finally, the eco-city should consider various resource factors of the town, reduce harmful substance discharge or domestic sewage as much as possible, and promote relevant policies to limit spontaneous emissions of related enterprises. The architectural and urban aspects of eco-city solutions are presented in Tables 1 (advantages) and Table 2 (disadvantages).

Table 1. Benefits of implementing energy recycling technologies in the urban context

Energy recycling: benefits

Reduced waste	Energy recycling can help reduce the amount of waste sent to landfills or incinerated. By recovering energy from waste materials, such as municipal solid waste, energy recycling can help to divert these materials from the waste stream, reducing the burden on landfills and decreasing the environmental impact of waste disposal.
Reduced greenhouse gas emissions	Energy recycling can also help to reduce greenhouse gas emissions. By recovering energy from waste, energy recycling can help to reduce the amount of fossil fuels that are burned to generate electricity, thereby cutting down on the emissions of greenhouse gases that contribute to climate change
Increased energy efficiency	Energy recycling can help to improve energy efficiency by capturing and reusing waste or unused energy. For example, waste heat from industrial processes can be recovered and used to generate electricity or to provide heating for buildings or other purposes
Cost savings	Energy recycling can also help to save money. By recovering energy from waste or unused sources, energy recycling can reduce the need to purchase fossil fuels for energy generation, thereby cutting energy costs
Job creation	The development and implementation of energy recycling technologies can also create new jobs and stimulate economic growth in the renewable energy sector
Energy security	By utilising a range of energy sources, including waste and other renewable sources, energy recycling can help to increase energy security and reduce dependence on imported fossil fuels

Table 2. Disadvantages of implementing energy recycling technologies in the urban context

Energy recycling: disadvantages	
Pollution and environmental impacts	Some forms of energy recovery, such as incineration, can produce emissions and pollutants that can have negative environmental impacts. If not properly managed, the emissions from energy recovery processes can lead to air and water pollution and contribute to climate change
High initial costs	The initial cost of installing energy recovery systems can be relatively high, which may be a barrier for some businesses or individuals looking to adopt these technologies
Limitations on the types of waste that can be used	Not all waste materials are suitable for energy recovery, and some materials may require additional processing or treatment to be used effectively
Potential for competition with other waste reduction strategies	Energy recovery can compete with different waste reduction strategies, such as recycling and composting. In some cases, these additional strategies may be more environmentally and economically beneficial than energy recovery
Destruction of the landscape by renewable energy technologies	Devices such as wind turbines and photovoltaic cells require large tracts of land to generate enough energy, causing significant interference with the landscape
Adverse side effects	In the case of shaping the building in such a way as to increase the strength of aerodynamic phenomena formed at the facility and use them to produce energy from wind, potential places are created that are unfavourable to pedestrians in the first floor part of the building

4. Energy recovery implementation technologies

Energy recycling is a process that involves capturing and utilising energy from waste materials or methods. Energy recycling has become an increasingly important strategy for reducing greenhouse gas emissions, improving energy efficiency, and promoting sustainable development. By focusing on waste management, energy efficiency, renewable energy sources, localised energy systems, and collaboration and partnerships, it is possible to create more sustainable and resilient energy systems that benefit both the environment and the economy

Architecture and urban planning are linked to the various stages of investment. Not all energy harvesting methods can be applied at every stage of construction. Most need to be thought about even before designing a building, creating guidelines for it - at the stage from central planning to architecture. The best results can be achieved by thinking about the proper development of facilities at the stage of development of municipal studies, Local Development Plans.

Part of the methods can be introduced during construction or into the existing urban fabric. Excluding activities that eliminate the development, current technologies allow to modernise the shells of buildings in this direction, retrofit them or introduce elements on the scale of small architecture or green to the urban space. Unfortunately, the later the stage of introduction of solutions, the smaller the scope they concern. Table 3 presents the main key aspects- a road map that must be addressed in designing and retrofitting at every step of the building life cycle.

Table 3. Disadvantages of implementing energy recycling technologies in the urban context

Key aspects of designing eco-city solutions in the architectural and urban context	
Waste management	Energy recycling is often closely linked to waste management, as many waste materials contain energy that can be harnessed. To effectively recycle energy, it is important to have a well-designed waste management system that separates recyclable and non-recyclable materials and organic and inorganic waste. Waste management practices that prioritise waste reduction, reuse, and recycling can help to minimise the amount of waste that is sent to landfill and can also reduce the energy required for waste disposal
Energy efficiency	To maximise the energy that is recovered from waste materials, it is important to focus on energy efficiency in all aspects of the energy recycling process. This includes designing energy-efficient systems for waste collection, transport, and processing and minimising energy losses during the energy conversion process. Energy-efficient technologies and practices can help to reduce greenhouse gas emissions and promote sustainable development
Renewable energy sources	Energy recycling is often combined with using renewable energy sources, such as solar, wind, or geothermal power, further reducing greenhouse gas emissions and promoting sustainable energy production. By combining energy recycling with renewable energy sources, it is possible to create a more sustainable and resilient energy system that is less reliant on fossil fuels
Localised energy systems	Energy recovery can compete with other waste reduction strategies, such as recycling and composting. In some cases, these additional strategies may be more environmentally and economically beneficial than energy recovery
Collaboration and partnerships	Energy recycling is often most effective when it is used to support localised energy systems. For example, a district heating system that utilises waste heat from a nearby industrial process can provide heat to nearby homes and buildings, reducing the need for fossil fuel heating systems. By creating localised energy systems that utilise energy from waste materials, it is possible to create a more efficient and sustainable energy system that is less reliant on centralised energy generation
Adverse side effects	Energy recycling often requires collaboration and partnerships between stakeholders, including waste management companies, energy companies, local governments, and communities. Effective collaboration and partnerships can help identify and address barriers to energy recycling and promote the development of integrated and sustainable energy systems. By working together, it is possible to create more sustainable and resilient communities that are less reliant on fossil fuels and more capable of meeting their energy needs

5. Conclusion and discussion

One of the key ways in which energy recycling and urbanism are linked is through the design and planning of urban infrastructure. Urban planners and engineers can incorporate energy recycling technologies into the design of buildings, transportation systems, and other urban infrastructure, helping to create more sustainable and energy-efficient cities. For example, buildings can be designed to capture and reuse waste heat or to generate electricity by solar panels or other renewable energy sources. Furthermore, energy recycling is being integrated into the design of new urban developments. For example, some cities are mandating the installation of eco-friendly solutions on new buildings. There are also demands to introduce urban retrofitting of old buildings and city infrastructures (such as solar-based streetlamps). This can help reduce the city's overall energy consumption and increase its reliance on renewable energy sources.

References

[1] S. Pincetl, P. Bunje, and T. Holmes, "An expanded urban metabolism method: Toward a systems approach for assessing urban energy processes and causes," *Landsc. Urban Plan.*, vol. 107, no. 3, pp. 193–202, 2012, doi: https://doi.org/10.1016/j.landurbplan.2012.06.006.

[2] P. Moonen, T. Defraeye, V. Dorer, B. Blocken, and J. Carmeliet, "Urban Physics: Effect of the micro-climate on comfort, health and energy demand," *Front. Archit. Res.*, vol. 1, no. 3, pp. 197–228, 2012, doi: https://doi.org/10.1016/j.foar.2012.05.002.

[3] A. Starzyk *et al.*, "Environmental and Architectural Solutions in the Problem of Waste Incineration Plants in Poland: A Comparative Analysis," *Sustain.*, vol. 15, no. 3, 2023, doi: https://doi.org/10.3390/su15032599.

[4] A. Ramos and A. Rouboa, "Renewable energy from solid waste: life cycle analysis and social welfare," *Environ. Impact Assess. Rev.*, vol. 85, no. July, p. 106469, 2020, doi: https://doi.org/10.1016/j.eiar.2020.106469.

[5] M. Zabarjad Shiraz, A. Dilimulati, and M. Paraschivoiu, "Wind power potential assessment of roof mounted wind turbines in cities," *Sustain. Cities Soc.*, vol. 53, p. 101905, 2020, doi: https://doi.org/10.1016/j.scs.2019.101905.

[6] A. S. Yang, Y. M. Su, C. Y. Wen, Y. H. Juan, W. S. Wang, and C. H. Cheng, "Estimation of wind power generation in dense urban area," *Appl. Energy*, vol. 171, pp. 213–230, 2016, doi: https://doi.org/10.1016/j.apenergy.2016.03.007.

[7] S. Acarer, Ç. Uyulan, and Z. H. Karadeniz, "Optimisation of radial inflow wind turbines for urban wind energy harvesting," *Energy*, vol. 202, 2020, doi: https://doi.org/10.1016/j.energy.2020.117772.

[8] I. F. Ballo, "Imagining energy futures: Sociotechnical imaginaries of the future Smart Grid in Norway," *Energy Res. Soc. Sci.*, vol. 9, pp. 9–20, 2015, doi: https://doi.org/10.1016/j.erss.2015.08.015.

A CASE STUDY OF BIM PROJECTS IN HOSPITAL CONSTRUCTION – COMPARING GERMANY TO THE INTERNATIONAL STATUS

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Abstract

The effective communication and coordination between all participants are a prerequisite for efficient project management. Especially in complex constructions, a high degree of coordination and communication is required due to an increased potential for errors in the project execution. Hospitals, as buildings of critical infrastructure, represent very complex constructions with increased regulations. Furthermore, there is an additional trade of medical technology, and an increased number of stakeholders need to be coordinated. The method Building Information Modeling (BIM) offers an efficient opportunity for transparent communication and provides a database of the building over its entire life cycle. In addition, there are many other use cases using BIM to benefit the management of the hospital, such as model-based quantity and cost determination or the use of a digital twin for facility management. BIM is becoming more established worldwide and also in the field of hospital construction BIM is already used. However, the scope of BIM application varies significantly among different projects, highlighting the need for a more detailed examination of existing or completed hospital projects.

This report compares various international hospital projects regarding the application of BIM whereas 10 out of 20 projects are in Germany. The information required for this case study is obtained by literature research. This provides an overview of the present state of BIM implementation in a global comparison, which provides the basis for the development of specific standards for the use of BIM in hospital projects. This enables the advancement of the implementation of BIM in hospital construction and the exploitation of the highest possible benefits over the entire life cycle to operate hospitals in a future-proof, sustainable and economical manner.

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Keywords: Building Information Modeling, hospital construction, project management, health care management, digitalization.

1. Introduction

1.1. Issue

Hospitals are highly complex buildings belonging to critical infrastructure and thus require a high degree of coordination and communication in the planning and execution of a construction project [1]. Due to the complexity of the buildings and a high number of project participants, there is an increased potential for errors in project execution.

The publication by Holzhausen et al. presents various ways how the digital method Building Information Modeling (BIM) can address the challenges of hospitals in the design and construction process [2]. By utilizing a common data environment, communication becomes more transparent and efficient compared to conventional design processes, thereby reducing the potential for errors. However, the use of BIM offers numerous applications beyond the design and construction phases of a project. The ability to use a digital twin throughout the entire lifecycle of a building (planning, execution, operation and deconstruction) enables numerous other improvements in terms of management processes, cost and risk minimization, as well as more efficient and sustainable workflows. In this regard, the relevance of BIM is emphasized, particularly for complex and cost-intensive buildings such as hospital construction, extending beyond all lifecycle phases.

Hartmann et al. describes the increasing significance of BIM at a global level and the associated mandatory requirements [1]. Standards are continuously refined and integrated into projects in terms of defined BIM objectives and use cases. The study demonstrates that this trend is also observable in hospital construction.

1.2. Purpose

The present study is conducted within the research project KlinikBIM, which aims to develop a guideline for the implementation of BIM in hospital construction in Germany. To formulate recommendations, it is necessary to analyze the German status quo and, in particular, to examine the international situation, particularly in countries where BIM application is more advanced than in Germany. Thus, both the BIM application in hospital projects in Germany and internationally are analyzed and compared. The objective of this study is to identify and evaluate the current state of practice and the development of BIM application in hospital construction, in order to incorporate these findings into the guideline creation process.

During the analysis of reference projects to determine the status quo of BIM implementation in hospital construction, notable differences were observed regarding the choice of BIM approach, specifically Big, Little, Open, and Closed BIM. Since understanding these terms is essential for comprehending this study, they will be briefly explained as follows: Big BIM refers to the interdisciplinary application of the BIM method over the entire life cycle of a building whereas Little BIM is a common term for the application of the BIM method limited to one discipline and thus describes an insular solution. In a data exchange strategy according to Open BIM, data is exchanged using open information models. An open information model is based on a disclosed schema. In an Open BIM approach, the software should be able to import or export data according to the open information model agreed upon in the project. Software from different manufacturers can be used. In Closed BIM, data is exchanged and integrated according to a software vendor's proprietary information model. A proprietary information model is based on a schema of the software manufacturer whose structure is not open ("Closed").

In this study, potential correlations between the projects and their BIM application will be analyzed. To achieve this, the following research questions have been formulated, which will be specifically addressed in the analysis of the results:

- Which BIM approach was chosen most frequently in the reference projects considered?
- Is the preferred approach different between national and international projects?
- Has the choice of BIM approach changed over time?
- Can a correlation be observed between project size and the choice of BIM approach?

These questions aim to explore patterns and trends in the BIM implementation within the considered projects. The analysis of these aspects will provide insights into the prevailing practices and potential influencing factors related to the selection of BIM approaches in hospital construction projects.

2. Method

This research report analyzes and compares ten international and ten German BIM projects in hospital construction based on defined parameters, which will be described in more detail later. As this paper focuses on a case study of reference projects in hospital construction, predominantly grey literature has been used since websites of the hospitals provided more up-to-date information on the projects compared to research articles. The methodology employed for literature research was unsystematic. The selection of the twenty reference projects constitutes a sample size, as further research identified a larger number of projects. Projects that provided sufficient information were included in the study. The selection criteria were the application of BIM, and it is a hospital building. Whether it involved an extension, a replacement, a partial new building or renovation did not matter for the selection. To ensure a comparison between German and international projects, an equal number was chosen for each. For a global assessment of the state of BIM implementation, a wide geographical distribution of international projects was considered. This approach aimed to include projects from various locations worldwide, ensuring a broader representation and understanding of the global landscape of BIM implementation in hospital construction. Once 20 reference projects were identified, a heterogeneous data set was obtained, leading to the conclusion of the search.

The selected projects were analyzed according to the following categories: Project start (design and construction), year of commissioning, number of beds, gross floor area, costs, and the chosen BIM approach. These categories were established based on initial research findings when formulating the research questions for this study, as listed in the previous chapter. These categories allow for a tabular comparison of the projects. If projects lacked information on these categories, contact persons (e.g., from architecture, planning offices or the hospitals) were contacted by mail to fill the gaps in the data. After receiving numerous responses, the data was mostly complete, enabling analysis. In order to indicate the BIM approach, the authors made interpretations in some cases when it could be inferred from the project description, BIM use cases, or BIM objectives. If data still could not be found, the cells were marked as "not available" (n.a.). The amount of missing data is considered minimal, therefore not significantly impacting the results of the study.

3. Results

3.1 Compilation of Data

In this chapter, the data obtained from the analysis will be presented in a tabular format, with Table 1 listing the German projects and Table 2 listing the international projects. The reference projects are listed in rows and corresponding information is organized in columns for the selected categories. It should be noted that the gross floor area has been rounded to 1,000 m², and the costs to millions of euros. In the case of international projects, where costs were given in a currency other than euros, these were converted on 12.04.2023 by using the European Commission's currency converter. The projects listed in this study are new buildings, some of which are replacements or extensions. However, the Mercy Jefferson Hospital (No. 8) and the Shanghai Xinhua Hospital Pediatric Complex (No. 9) include data for both new construction and partial renovation of existing buildings.

Table 1. Overview data on German projects (1 = Klinikum Wilhelmshaven, 2 = GEH II R.K. Gehrden, 3 = Campus Zentralklinikum Lörrach, 4 = Klinikum Frankfurt Höchst, 5 = Flugfeldklinikum Sindelfingen, 6 = ALB FILS Klinikum am Eichert, 7 = Prosektur Uniklinikum Köln, 8 = Cnopfsche Kinderklinik, 9 = Jüdisches Krankenhaus Berlin, 10 = US Hospital Weilerbach; n.a. = not available)

No.	Start of design [yr]	Start execution [yr]	Commis-sioning [yr]	Total number of beds [Pcs.]	Cross floor area [k m²]	Total costs [€]	BIM approach
1	2015 [3]	2021 [3]	2025 [4]	500 Pcs.* [4]	51.565 m²* [4]	194, 1 Mio. [3]	Little Closed BIM [3]
2	2019 [5]	2024 [5]	2027 [5]	250 Pcs. [5]	36 k m² [5]	234 Mio.€ [5]	Big Open BIM [5]
3	2018 [6]	2020 [6]	2025 [6]	677 Pcs. [6]	90 k m² [6]	430 Mio.€ [6]	Big Open BIM [6]
4	2007 [7]	2016 [7]	2023 [7]	670 Pcs. [7]	80 k m² [7]	263 Mio.€ [7]	Little Open BIM [7]
5	2018 [8]	2021 [8]	2025 [8]	700 Pcs. [8]	110 k m² [8]	573 Mio.€ [8]	Big Open BIM [8]
6	2014 [9]	2019 [10]	2024 [10]	688 Pcs. [9]	94 k m² [9]	455 Mio.€ [10]	Little Open BIM [10]
7	2016 [11]	2022 [11]	2024 [11]	0 Pcs. [11]	9 k m² [11]	76 Mio.€ [11]	Big Open BIM [11]
8	2018 [12]	2021 [13]	2027 [12]	72 Pcs. [12]	11 k m² [12]	90 Mio.€ [14]	Big Open BIM [15]
9	(n.a.)	2021 [16]	2024 [16]	214 Pcs. [16]	11 k m² [16]	50 Mio.€ [16]	Big BIM [17]
10	2011 [18]	2014 [18]	2028 [18]	68 Pcs. [18]	120 k m² [18]	1100 Mio.€ [18]	Big Open BIM [18]

* These numbers are not final, as planning changes are currently being made.

Table 2. Overview data on international projects (11 = Aarhus University Hospital in Denmark, 12 = Sykehuset Østfold Hospital in Norway, 13 = Dr Pixley Ka Isaka Seme Memorial Hospital in South Africa, 14 = New Surrey hospital and BC Cancer in Canada, 15 = Whipps Cross Hospital London in UK, 16 = Queen Silvia Children's Hospital in Sweden, 17 = Royal Adeleide Hospital in Australia, 18 = Mercy Jefferson Hospital in USA, 19 = Shanghai Xinhua Hospital Pediatric Complex in China, 20 = Spital Limmattal in Switzerland; n.a. = not available)

No.	Start of design [yr]	Start execution [yr]	Commis-sioning [yr]	Total number of beds [Pcs.]	Cross floor area [k m²]	Total costs [€]	BIM approach
11	2008 [19]	2013 [19]	2019 [19]	797 Pcs. [19]	216 k m² [19]	852 Mio.€ [19]	Big Closed BIM [19]
12	2008 [20]	(n.a.)	2015 [21]	(n.a.)	86 k m² [20]	442 Mio.€ [22]	Open BIM [22]
13	2003 [23]	2015 [24]	2021 [24]	500 Pcs. [25]	29 k m² [25]	150 Mio.€ [26]	BIM [27]
14	2019 [28]	2023 [29]	2027 [29]	168 Pcs. [28]	(n.a.)	1156 Mio.€ [30]	Big Open BIM [31]
15	2021 [32]	2023 [32]	2026 [32]	500 Pcs. [33]	78 k m² [34]	452 Mio.€ [35]	Big Open BIM [36]
16	2010 [37]	2015 [37]	2020 [37]	112 Pcs. [37]	33 k m² [37]	133 Mio.€ [37]	Big Open BIM [37]
17	2009 [38]	2011 [39]	2017 [39]	800 Pcs. [40]	175 k m² [38]	1117 Mio.€ [41]	Big BIM [41]
18	2013 [42]	(n.a.)	2015 [43]	90 Pcs. [42]	11 k m² [44]	66 Mio.€ [44]	Open BIM [45]
19	(n.a.)	(n.a.)	2020 [46]	472 Pcs. [47]	58 k m² [46]	(n.a.)	Big BIM [46]
20	2012 [48]	2014 [48]	2018 [48]	324 Pcs. [48]	49 k m² [48]	254 Mio.€ [48]	Open BIM [48]

3.1. Evaluation and interpretation of results

In this chapter, the data analysis is presented graphically to provide answers to the research questions from Chapter 2.1. These results will be interpreted subsequently. For better clarity, the graphs will only display the project numbers from Tables 1 and 2, and not the project names.

To address the research question of which BIM approach was most commonly chosen in the analyzed reference projects, Figure 1a was created, which includes all results regarding the selected BIM approach, even if no information was provided. This graph reveals that the Big Open BIM approach was particularly favored. To answer the question "Is the preferred approach different between national and international projects?", Figure 1b was generated. To improve clarity, the representation of missing data was omitted in this graph. From this figure, it is evident that both internationally and nationally, the Big Open BIM approach is favored.

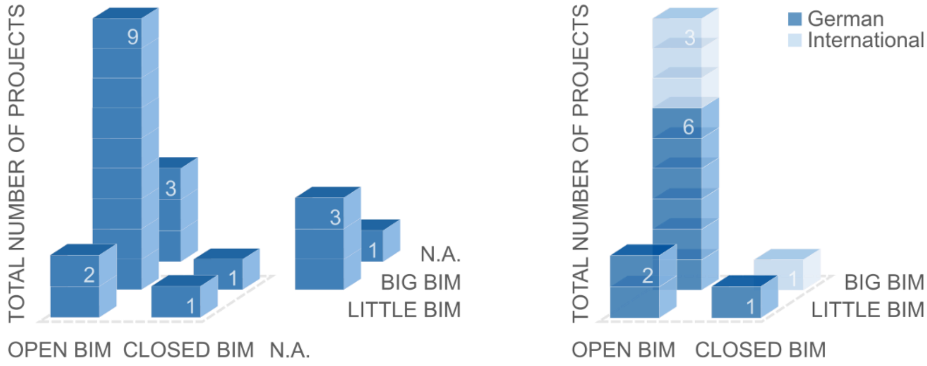

Fig. 1 (a) BIM approaches of the 20 hospital projects. (b) Use of BIM approaches in Germany and internationally

Figure 2 illustrates the adoption of BIM approaches over time, separately for German and international projects. The analysis is based on the start of the planning phase rather than the execution phase, as the BIM approach is chosen at this stage. When comparing the German and international projects regarding the start of design, it is noticeable that the progression is shifted by approximately two years.

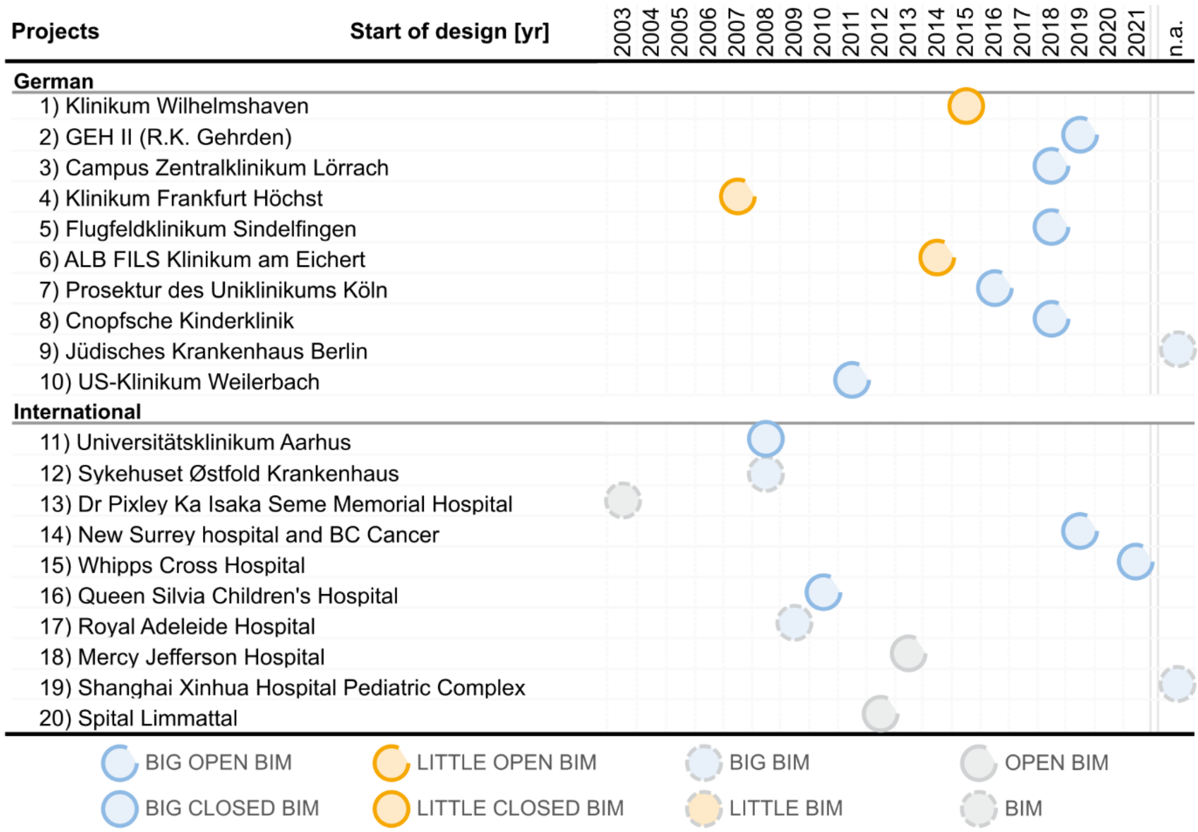

Fig. 2 Comparison of national and international hospital projects under consideration of the chosen BIM approach over time

This confirms the statement from the final report of the project "International experiences: Future Cities and BIM" of the University of Cambridge: "Whilst Germany is relatively behind in the usage of BIM in international comparison since 2015 there has been considerable movements driven by the Ministry for Transport and Digital Infrastructure. The Ministry announced a BIM mandate for 2020 in 2015. This mandate requires that all projects under the responsibility of the Ministry use BIM by 2020. BIM entered public procurement rules in April 2016. A BIM working group was developed named planen bauen 4.0, which had the essential task to roll-out a plan for BIM." [49, p. 18] Following the mandate for the introduction of BIM in infrastructure projects, Germany has implemented further strategies for BIM application. For instance, the Masterplan BIM for Federal Buildings [50] and the Masterplan BIM for

Federal Highways [51], both published in 2021. Furthermore, based on this graph, it can be observed that from 2016, the Big Open BIM approach was exclusively chosen. Incomplete or missing information was appropriately labeled.

Figure 3 presents the analysis regarding the investigation of a potential relationship between the BIM approach and project size. Since project size can be measured based on cost, gross floor area, and number of beds, these parameters are shown next to each other, with the project numbers indicated. Projects where the BIM approach was not fully specified were not included in this representation. Due to the unavailability of data on the gross floor area for the New Surrey Hospital at BC Cancer and the absence of beds in the Prosektur of the University Hospital Cologne, they were not listed in their respective categories. The diagram does not reveal a clear correlation between project size and the chosen BIM approach. Upon closer examination, it is noticeable that in Aarhus University Hospital Cross floor area and Total number of beds represents the largest project and in the Total costs category the second largest project and the Big closed approach was used. However, in the other two largest projects in the respective categories, the Big Open BIM approach is used. However, in the other two largest projects in the respective categories, the Big Open BIM approach is used. Given the limited number of Little and Closed projects and the high number of Big and Open BIM approaches, this study does not identify a relationship between project size and BIM approach. A larger sample would be necessary to draw conclusions in this regard.

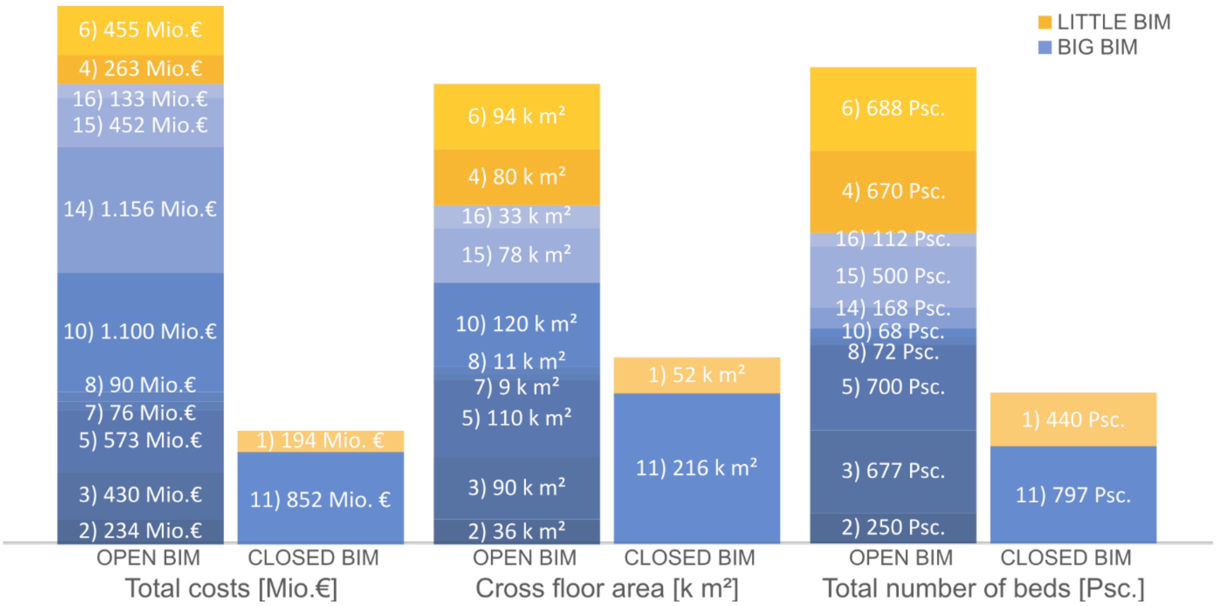

Fig. 3 Correlation between project size and the chosen BIM approach whereby the blue tones represent the Big BIM approach, and the orange tones the Little BIM approach

4. Conclusion

The results of this study demonstrate that BIM is already being applied in hospital construction in both Germany and internationally, although it is not yet the norm. In this study, ten national and ten international projects were analyzed to assess the current state of practice in Germany and compare it to international projects. While this sample appeared sufficient for an assessment of the current state, a comprehensive study encompassing all existing BIM projects in hospital construction would be required to confirm the findings. In summary, the implementation of BIM projects in this sample began on average approximately two years earlier in international projects compared to Germany. The Big Open BIM approach was predominantly chosen for the analyzed projects, both nationally and internationally, whereby the choice of BIM approach did not exhibit any dependencies on project size in this study. Particularly in recent projects from 2016 onwards, the Big Open BIM approach was exclusively applied, whereas earlier BIM projects in hospital construction occasionally choose other approaches. This trend and the preference for the Big Open BIM approach can be attributed to the added value of BIM, particularly in terms of collaboration and software interoperability throughout the entire lifecycle of the building.

Acknowledgement

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References

[1] S. Hartmann, C. Patberg and K. Klemt-Albert, "Opportunities and challenges of Building Information Modeling in hospital construction“ in Conference Proceedings of the 6th International Conference on Healthcare Service Management (ICHSM), Kyoto, Japan, 2023.
[2] C. Roth, U. Dombrowski, and M. N. Fisch, Eds., “Zukunft. Klinik. Bau.,” 2015, doi: 10.1007/978-3-658-09988-6.
[3] M. Schoof, Personal correspondence, 15.03.2023.
[4] "Zahlen, Daten, Fakten“ https://www.klinikum-whv.de/unternehmen/neubau/zahlen_daten_fakten.php (Access date: 12.04.2023)
[5] T. Buge, Personal correspondence, 11.03.2023.
[6] T. Stolpe, Personal correspondence, 11.03.2023.
[7] S. Böhme, Personal correspondence, 11.03.2023.
[8] E. Dehoust, Personal correspondence, 05.05.2023.
[9] "Klinikbau am Eichert: Alles zum neuen Krankenhausgebäude und den Teilprojekten“ https://www.alb-fils-kliniken.de/fileadmin/default/80_Ueber-uns/Imagebroschuere_ALB_FILS_KLINIKEN.PDF (Access date: 13.05.2023)
[10] "Alles zum neuen Krankenhausgebäude und den Teilprojekten“ https://www.alb-fils-kliniken.de/neubau/neubau-klinik-am-eichert/ (Access date: 13.05.2023)
[11] U. Lörch, Personal correspondence, 31.03.2023.
[12] "Sanierung und Erweiterung Klinik Hallerwiese und Cnopf'sche Kinderklinik" https://www.dreso.com/de/projekte/details/sanierung-und-erweiterung-klinik-hallerwiese-und-cnopfsche-kinderklinik (Access date: 13.05.2023)
[13] Drees & Sommer SE, "Klinikum Hallerwiese und Cnopfsche Kinderklinik“ (in German), Bauen + Wirtschaft – Architektur der Region im Spiegel, pp. 88-89, Franken, Germany: WV Wirtschafts- und Verlagsgesellschaft mbH, 2021, ISBN 978-3-949158-01-8
[14] Franken Fernsehen. "Cnopfsche Kinderklinik wird für 90 Millionen Euroausgebaut“ (in German). (04.03.2020). https://www.frankenfernsehen.tv/mediathek/video/cnopfsche-kinderklinik-wird-fuer-90-millionen-euroausgebaut/ (Access date: 13.05.2023)
[15] M. Küpper, Personal correspondence, 20.07.2022.
[16] "Neubauprojekt Bettenhaus Jüdisches Krankenhaus Berlin“ https://www.jkb-neubau.de/ (Access date: 13.05.2023)
[17] "Jüdisches Krankenhaus Berlin" https://www.obermeyer-group.com/referenzen/detail/juedisches-krankenhaus-berlin (Access date: 13.05.2023).
[18] U. Choscz, Personal correspondence, 28.03.2023.
[19] M. Dammann, Personal correspondence, 13.04.2023.
[20] "Arkitema Østfold Hospital" https://www.arkitema.com/en/project/østfold-sygehus (Access date: 25.04.2023)
[21] "Case Study, New Østfold Hospital project“ https://buildingsmart.org/wp-content/uploads/2017/07/Ostfold-2015-final-version-30012015.pdf (Access date: 25.04.2023)
[22] "A strategy for use of BIM during the assets life cycle & case study from the New Østfold Hospital" https://static1.squarespace.com/static/5cd993d1b10f253cf1e619bd/t/5d014bf13567060001a2496a/1560366097028/BirgerStamso_HSO_BIM_Strategy1.pdf (Access date: 13.05.2023)
[23] "Dr. Pixley Ka Isaka Seme Memorial Hospital“ http://www.kznhealth.gov.za/DPKISMH.htm (Access date: 13.05.2023)
[24] "Dr Pixley Ka Isaka Seme Memorial Hospital“ https://enzacon.co.za/portfolio/dr-pixley-ka-isaka-memorial-hospital/ (Access date: 13.05.2023)
[25] "Supporting Kwa-Zulu Natal's hospital revitalization programme“ https://www.zutari.com/project/dr-pixley-ka-isaka-seme-memorial-hospital/ (Access date: 13.05.2023)
[26] "Enza Construction nears completion of R3bn Dr Pixley Ka Isaka Seme Memorial Hospital“ https://www.constructionsafety.co.za/2019/08/13/enza-construction-nears-completion-of-r3bn-dr-pixley-ka-isaka-seme-memorial-hospital/ (Access date: 13.05.2023)
[27] "Dr. Pixley Isaka Seme Memorial Hospital fast-tracked for June opening“ https://www.bizcommunity.com/Article/196/757/204555.html (Access date: 13.05.2023)
[28] Fraser Health Authority, "Project overview“ https://www.fraserhealth.ca/your-community/surrey/new-surrey-hospital-project/overview#.ZC1fKi-21QI (Access date: 13.05.2023)
[29] Infrastructure BC, "New Surrey Hospital & BC Cancer Centre Project“ https://www.infrastructurebc.com/projects/announced-in-procurement/new-surrey-hospital-cancer-centre/ (Access date: 13.05.2023)
[30] "New hospital, BC Cancer Centre in Surrey moves forward“ https://news.gov.bc.ca/releases/2022HLTH0156-001048 (Access date: 13.05.2023)

[31] "BIM and a $1.72bn hospital project in Canada“ https://www.bimacademy.global/insights/project-management/dr-melanie-robinson-talks-bim-and-a-1-72bn-hospital-project-in-canada/ (Access date: 13.05.2023)

[32] "Whipps Cross Hospital Development“ https://www.walthamforest.gov.uk/regeneration-and-growth/regeneration-projects-and-developments/regeneration-leytonstone/whipps-cross-hospital-development (Access date: 13.05.2023)

[33] "Safe and sustainable clinical services“ https://hoarelea.com/project-story/whipps-cross-hospital-london/ (Access date: 13.05.2023)

[34] "Design Team Appointed for the New Whipps Cross Hospital“ https://www.ryderarchitecture.com/design-team-appointed-for-the-new-whipps-cross-hospital/ (Access date: 13.05.2023)

[35] "Whipps Cross Hospital“ https://www.bimacademy.global/work/whipps-cross-hospital/ (Access date: 13.05.2023)

[36] "Intelligent Hospital Design Principles“ https://hoarelea.com/app/uploads/2021/06/Intelligent_Hospitals_Design_Principles.pdf (Access date: 13.05.2023)

[37] K. Nilsson, Personal correspondence, 30.03.2023.

[38] "New Royal Adelaide Hospital“ https://www.hansenyuncken.com.au/images/projects/health/new-royal-adelaide-hospital/HY%20100%20Years%20-%20the%20new%20Royal%20Adelaide%20Hospital.pdf (Access date: 13.05.2023)

[39] "New Royal Adelaide Hospital“ https://www.cpbcon.com.au/en/our-projects/2011/nrah (Access date: 13.05.2023)

[40] "Delivering New Royal Adelaide Hospital with BIM“ https://www.bimmodel.co/single-post/2016/08/22/delivering-new-royal-adelaide-hospital-with-bim (Access date: 13.05.2023)

[41] "Royal Adelaide Hospital Australia and BIM“ https://www.modlar.com/blog/royal-adelaide-hospital-australia-and-bim/ (Access date: 13.05.2023)

[42] "Mercy Hospital Jefferson“ https://theljc.com/projects/mercy-hospital-jefferson (Access date: 13.05.2023)

[43] "Mercy Hospital, Jefferson, A Smart Building Solution“ https://library.e.abb.com/public/b8a96c43368141b9a0aa8feeeb72cc19/ABB_Cylon_A4_170301_MercyHospitalJefferson_CaseStudy_global.pdf (Access date: 13.05.2023)

[44] "New Patient Tower and Renovations at Mercy Hospital Jefferson“ https://www.mccarthy.com/insights/new-patient-tower-and-renovations-mercy-hospital-jefferson (Access date: 13.05.2023)

[45] "Construction Complete on New Patient Tower at Mercy Hospital Jefferson“ https://hconews.com/2018/04/02/construction-complete-new-patient-tower-mercy-hospital-jefferson/ (Access date: 13.05.2023)

[46] "Medical Special: "Efficient and Intensive Smart Hospital"-Shanghai Xinhua Hospital Pediatric Complex“ http://zhubo.com/en/news/boutique-zhubo/550.html (Access date: 13.05.2023)

[47] "Xinhua Hospital“ http://zhubo.com/en/work/medical-treatment-and-pension/367.html (Access date: 13.05.2023)

[48] R. Wagner, Personal correspondence, 13.04.2023.

[49] F. Sielker and P. Allmendinger, "International experiences: Future Cities and BIM“ Cambridge, United Kingdom: University of Cambridge, 2018.

[50] Federal Ministry of the Interior and Community, „Masterplan BIM für Bundesbauten“ (in German), Berlin, Germany: Federal Ministry of the Interior and Community Publications, 2021.

[51] Federal Ministry for Digital and Transport, „Masterplan BIM Bundesfernstraßen“ (in German), Berlin, Germany: Federal Ministry for Digital and Transport Publications, 2021.

[52] "Flugfeldklinikum Böblingen-Sindelfingen 2023“ https://www.h4a-architekten.de/de/projekte/flugfeldklinikum (Access date: 13.05.23)

[53] "Royal Adelaide Hospital Australia and BIM“ https://www.modlar.com/blog/royal-adelaide-hospital-australia-and-bim/ (Access date: 13.05.2023)

Research on workflow improvement in the early stage of apartment design using BIM

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Abstract

The purpose of this study is to investigate a specific and effective study process for communicating the benefits of using BIM in apartment design to clients and designers. The study uses the initial stage of apartment design as an example. Even in the initial stages, the study includes important points for using BIM, and the ideas presented here are applicable to the subsequent design process. Based on the analysis of several real-life projects, the following discrepancies were found between the accuracy of the S0 and S1 stage considerations and the results in apartment design, it is common for the overall review and the dwelling unit review to be conducted in parallel from an early stage. This wide range in the scale of the review was one of the reasons for the discrepancy. And our previous research suggested the effectiveness of BIM's "group" function. By assigning object groups to the actual workflow, the review work required in thie S0 and S1 phases was clarified. By considering dwelling units, the building span can be determined. Therefore, spatial volume "groups" are used for the overall study, and 2D area object "groups" are used for the study of dwelling units. This process can be interpreted as reproducing the skeleton and infill on the BIM data. Furthermore, two methods, "landscape simulation" and "quantity calculation," are provided to objectively evaluate the study design results in S1. Visual programming allows for rapid study.

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Keywords: benefits of using BIM, apartment design, group of BIM objects, skeleton and infill, visual programming

1. Research overview

1.1. Widening digital gap in Japan

In Japan, the standard rules necessary for conducting BIM work are beginning to be defined. For example, a “BIM Promotion Roundtable” led by the Ministry of Land, Infrastructure, Transport and Tourism was established in 2020, and the “Design BIM Workflow Guidelines (1st Edition)” were published in 2021. [1] Meanwhile, small and medium-sized enterprises with no extra staff or budget to spare have been left behind in the process of introducing BIM, resulting in a widening digital gap between these enterprises and large corporations that have ample workforce and budget. One of the reasons given by small and medium-sized enterprises for not introducing BIM is because they cannot understand its benefits, and therefore cannot make the decision to introduce it. [2] Thus, explaining the specific benefits of BIM to the small- and medium-sized enterprises is necessary to make BIM more prevalent among Japanese businesses.

1.2 Purpose of this research

The purpose of this research is to investigate a specific and effective examination process for explaining the benefits of using BIM in apartment design to clients and contractors. Using the apartment building type as a specific example, we aim to improve workflow while incorporating the characteristics of apartment design and the analysis of the structural features of BIM. We believe that the improvement in the workflow will lead to optimization of businesses overall, benefiting both clients and contractors.

As a background, the system of ordering building construction in Japan is discussed herein. Internationally, separate ordering is common; however, in Japan, a lump sum contract is the most common process. In a lump sum contract, coordination between different construction steps is performed by a general contractor, who is the primary contractor for the project. Conventionally, the designer is responsible for coordinating the internal consistency of each section, namely the design, structure, and facility (i.e., the consistency among drawings such as plans, elevations, sections, and details). Moreover, the ensuring consistency between design and structural drawings (i.e., the positions of columns and beams) as well as the consistency among design, structural, and facility drawings (e.g., ensuring space for large facilities and measures against their load) is also the responsibility of the designer. However, the consistency among small equipment, such as the positions of air conditioning outlets or lighting on the ceiling, is coordinated by the general contractor during the production design stage prior to construction. In Japan, the level of detail required from drawings and specifications is “the level of detail that allows the calculation of accurate construction cost.” While the capability and number of equipment are accurately defined, detailed adjustment of their precise positions is assigned to the production design stage. The small adjustments in terms of cost that occur during the adjustments in the production design stage (e.g., the slight extension of pipes owing to minor adjustments in equipment position) are not ordinarily reimbursed. In a lump sum contract, the expenses borne by the general contractor (adjustment costs) are added to the contract, unlike in separate ordering; however, the client can avoid these financial risks during the construction stage by paying the “expenses” as insurance.

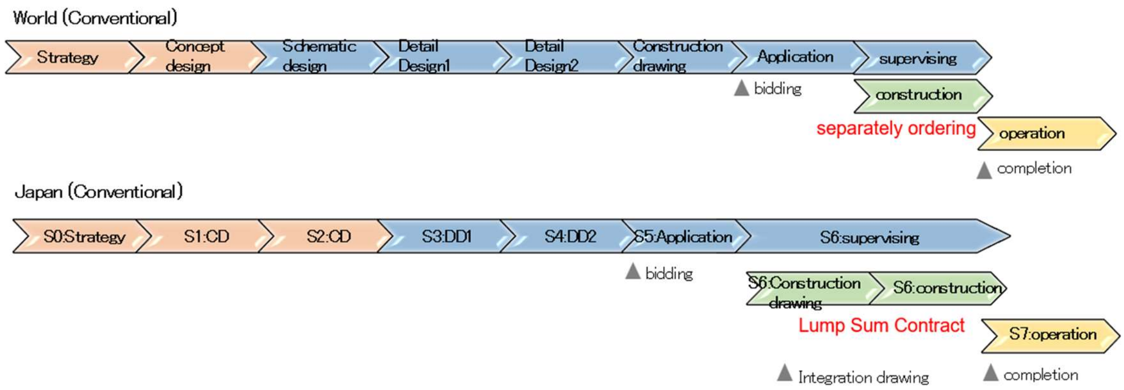


Fig. 1 The system of ordering building construction in Japan

The result of surveys conducted in other countries often mention that “ordering BIM reduces inconsistency among order drawings, thereby reducing the risk of increase in costs during the construction stage,” and list this fact as one of the benefits of introducing BIM for clients. However, this benefit is not always relevant in Japan, where lump sum contracts are common. Therefore, in Japan, while designers in large companies are increasingly using BIM, clients are still not keen on using BIM.

1. 3. Research method

In this study, apartments were used as specific examples in the design stage of apartment buildings. Considering the situation in Japan, explaining the benefits of using BIM at each stage to clients is important. In other words, clients need to receive some kind of benefits of BIM used during the design stage in the same stage, rather than to receive in a subsequent stage for example in the form of reduction of risks in the construction stage. Moreover, the fact that the data can be used in maintenance has been suggested as a benefit of using BIM for the clients. However, in a building with a small proportion of common-use space and small number of common facilities, such as an apartment building, realizing the benefits of using BIM in terms of maintenance requires ~10 years. Furthermore, the main construction process in large-scale renovation planning where usage of BIM is expected to have a substantial effect is the exterior wall renovation planning process. However, in this process, knowing only the shape of the exterior walls and their materials is sufficient, and a highly detailed model is not always necessary. Thus, the benefits of using BIM in this process are extremely limited. In this study, the benefits of using BIM in designing apartment buildings from the perspective of clients are demonstrated to encourage an increase in the usage and specification of BIM by clients in Japan.

This study uses the initial stage of an apartment design as an example. The important points of using BIM are included, even in the initial stage, and the concept presented herein can be applied to subsequent design processes.

As the first step of examination, the basic plan was divided into two stages: “S0” and “S1,” according to the “BIM guidelines” and these two stages were examined.

(1) Workflow analysis based on actual cases

(2) Understanding the features of apartment design

(3) Application of the structural characteristics of BIM

(4) Assign to the real workflow

Although we used the example of a tabular apartment rebuilding project undertaken by the Urban Renaissance Agency, we ensured that the process can be widely applied to apartment design in general. Autodesk Revit 2022 was used as the BIM software, which was packaged along with the visual programming Dynamo software.

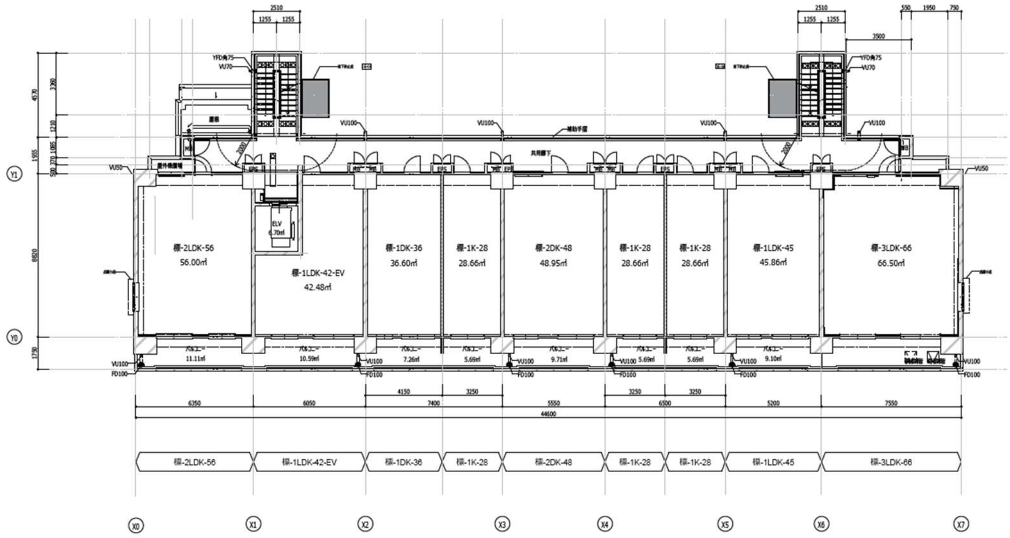


Fig. 2 Floor plan of the apartment used for research

2. Improved workflow

2.1. The analysis of the current situation

The purpose of the S0(strategic definition) and S1 (preparation & concept design) stages in the designing of an apartment building is to prepare and examine materials for determining whether the project can be started and to establish the design conditions necessary for S2 (preliminary design). Based on the analysis of several real-life projects, the following discrepancies were observed between the examination of the S0 and S1 stages and the precision of the outcome.

Examples of examination when S0 is complete:

Case 1: Set the target area and the number of dwelling units without preparing a specific construction plan. A rough estimate based on the estimated area is obtained.

Case 2: In addition to Case 1, examine roughly building layout based on the exterior appearance and floor number.

Examples of examination when S1 is complete:

Case 1: Examine the building layout based on the exterior appearance and floor number, and set the planned area. Define the number of dwelling units on one floor based on the standard span and set the number of dwelling units. Moreover, examine a building layout impression based on the exterior appearance and floor number.

Case 2: In addition to Case 1, set the dwelling unit types and the number of each unit type.

Case 3: In addition to Case 2, set specific span allocations and arrange the planning of unit types.

These discrepancies affect the subsequent stages substantially. Many real projects set the period for re-evaluation of the previous stage at the start of each new stage in their schedules.

While structural designers and facility designers enter the team in the S2 stage, they are made to wait for the first two months. Hence, the number of meetings increases. In the initial design stage, the responsibility of a client involves determining the given design conditions through discussions with designers. Attending these meetings and checking the agenda for these meetings is extremely time consuming. As the number of meetings increases, the labor borne by the client also increases. Hence, eliminating the discrepancies among examinations, preventing these examinations from being carried over to subsequent stages, and reducing the number of meetings is necessary. Moreover, increasing the efficiency of the examinations, preparing multiple alternative plans in a short amount of time, and discovering the optimal solution for a given project will be highly beneficial for both the client and the designers.

2.2. Characteristics of Apartment design

The design study flow of common office buildings moves from study at a large scale to study at a small scale; for instance, from the study of volume/layout (the scale used in the drawing would be ~1/400), study of the basic plan (about 1/200), interior and external details (~1/100 or 1/50), and section details (~1/20 or less). However, in an apartment design, the overall study (~1/400 or 1/200) and dwelling study (~1/100 or 1/50) are typically conducted in parallel from an early stage. Setting the “dwelling unit type” at the S1 stage necessitates study at a small scale even though it is in the initial stage of planning. This wide range in the study scale was one of the reasons why discrepancies could easily occur.

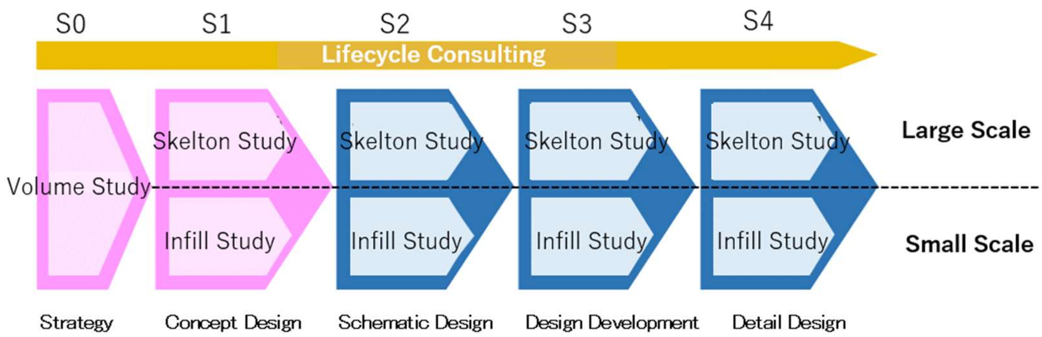


Fig. 3 Characteristics of Apartment design

2.3. Structural characteristics of BIM

A previous study by Iwamura suggested the effectiveness of the “group” function of BIM. [3]

Various other studies suggested that the uniqueness of BIM is in the fact that it possesses shape and information, and the authors strongly agree with that suggestion. However, that is not the only feature of BIM. We believe that the greatest benefit of BIM is the fact it has a mechanism that can perfectly reproduce the mechanism of a supply chain.

First, BIM has two environments: one to construct building models and another to produce components and equipment. The relation between these two environments is analogous to the relationship between a “construction site” and “factory.” Even in case of real-life building projects, not many components are produced from scratch on site. Buildings are constructed by bringing the components and facilities produced in factories to the site and then arranging them on site. This is also the case with respect to BIM models. Buildings are constructed by arranging the component and facility objects that produced in the object production environment at the site environment. The main task undertaken at the site environment is “arrangement.” BIM possesses shape and information. To describe this more accurately, BIM is an “assembly of objects that possess shape and information.”

Next, objects have a mechanism called a “group.” For example, the production of a shelf involves the preparation of plates at a material processing plant, which are then assembled into a shelf at an assembly plant; however, a BIM object can be produced in a single process. Producing plate objects in the first object environment, and then “nesting” and assembling these plate objects into a shelf object in the second object environment is possible. The shelf object is produced as a “group” of the plates. Through production using this “group” function, integrating the control items at each factory (material plant/assembly plant) into objects as attribute information becomes possible. The reason why one can regard BIM as the workflow itself, instead of a mere tool, is because BIM is capable of reproducing the workflow perfectly.

In addition to this “group” of nests, BIM has functions to create “groups” of groups, and “groups” of timelines. Moreover, as BIM is a digital space, it is capable of creating a “group” of combinations that would not be able to support itself in the real world. For instance, extracting only the floor material, wallpaper, and ceiling material of a room and turning them into a “group” object produced in the shape of the room is possible. Creating an object at the design stage that extracts only the items to be examined in the design, expedites the examination, and then divides it into individual objects after the completion of the examination. In addition, BIM is capable of producing a type of object called “space volume” that does not exist in reality and can create “groups” of these “space volume” objects. [4]

2.4. Utilization of two different "group" objects

The span of a tabular apartment building with a walled frame structure, which is the subject of this study, is determined by the width of a dwelling unit. Because earthquake-resistant walls are installed for each span, in principle, nearly identical dwelling types are layered from lower to upper floors. Taking this characteristic of the building type into account, space objects, wherein each span was vertically divided, and a space object “group,” where these objects were nested and arranged horizontally were produced for this study. Parametric transformation is possible using the span width and floor number as parameters. In addition, the total number of dwelling units and the floor space necessary for planning are calculated automatically.

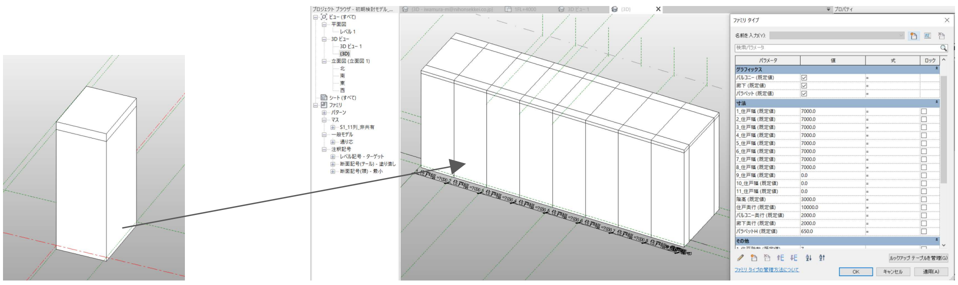


Fig. 4 "Group" suitable for initial stage overall plan review

The above is a "group" that speeds up the review of the overall plan, but we also created a "group" for reviewing the housing unit plan. For this creation, we used a 2D region object called “Filled Region” in

Revit. Again, each room area is grouped in a 2D object environment, and each room is grouped into a dwelling unit object. 2D region object has area information, and it is possible to arrange planning of a dwelling unit while confirming the area value.

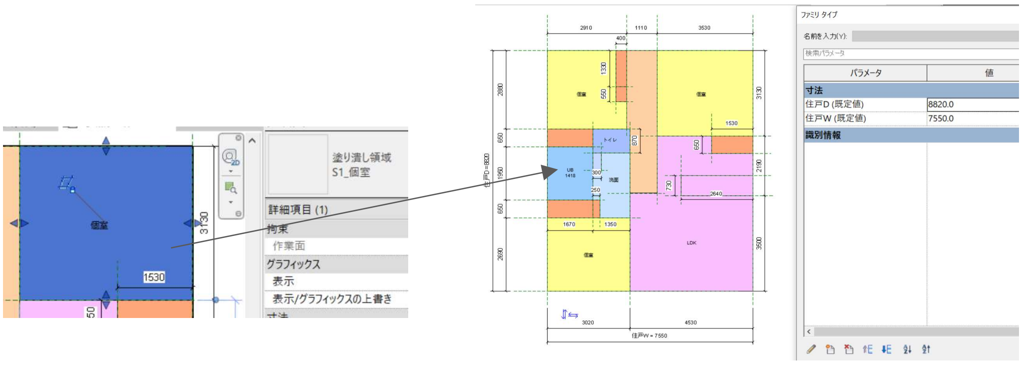


Fig. 5 "group" suitable for the initial stage of residential unit planning

2.5. Assign to the real workflow

The object groups were assigned to a real workflow to clarify the examination tasks required at the S0 and S1 stages.

2.5.1. Assign to S0

In S0, the space volume "group" and the average dwelling unit type width were applied to all the spans and used as "uniform span" models for the examination.

In S0, setting the layout of dwelling units in the plot, the approximate span width, and the number of floors is necessary. Through this setting, estimating the number of dwelling units that can be secured in the building becomes possible.

To expedite the workflow, not mixing up the study of dwelling unit width immediately at the S0 stage is important. Conventionally, even though it is only the initial study, adjustment of the dwelling unit span was conducted at the S0 stage. This occasionally led to delays in the study. Usage of the "uniform span model" would prevent such confusion.

Due to the nature of Japanese urban planning, in areas primarily designated for housing, the amount of shadow cast by a building within in a plot inside the area designated mainly for housing is regulated. In this study, visual programming "Dynamo" is used to improve efficiency.

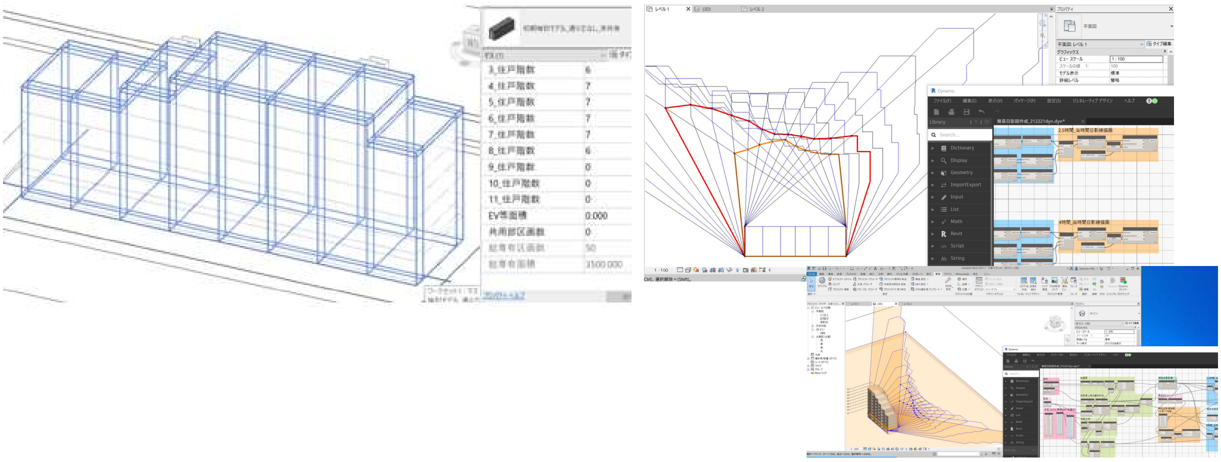
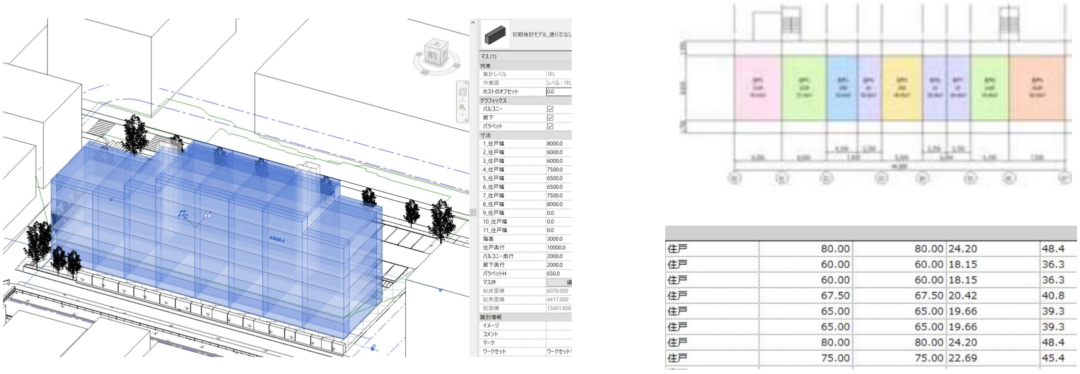


Fig. 6 Spatial volume placement and shadow simulation

The figure below shows the total number of dwelling units and the estimated total planned floor space calculated using the aggregation function of BIM after examining the residential buildings layout and residential building volume.



住戸	80.00	80.00	24.20	48.4
住戸	60.00	60.00	18.15	36.3
住戸	60.00	60.00	18.15	36.3
住戸	67.50	67.50	20.42	40.8
住戸	65.00	65.00	19.66	39.3
住戸	65.00	65.00	19.66	39.3
住戸	80.00	80.00	24.20	48.4
住戸	75.00	75.00	22.69	45.4

Fig. 7 Study on spatial volume "group" at S0

2.5.2. Assign to S1

Based on the overall study in S0, study of the dwelling unit(s) is conducted in S1 in parallel to the overall study. By study the dwelling unit, determining the building span becomes possible. Therefore, the space volume “group” is used for the overall study, and the 2D region object “group” is used for the study of dwelling unit. The data is structured using the phase function of Revit to conduct these two kinds of studies simultaneously. The phase function is highly useful for creating the construction animation, wherein the construction step information is input to the architectural components and MEP facilities of the BIM model (at which step they are used for the construction) to visualize the construction process plan. This phase function facilitates setting up of two steps: the overall plan and the dwelling unit plan and overlay the respective data. This process can be interpreted as a reproduction of the skeleton and infill on the BIM data. Theoretically, the relationship between the skeleton and the infill is a temporal, the infill is constructed after the skeleton, so it is natural that it has a high affinity with the phase function, which is temporal.

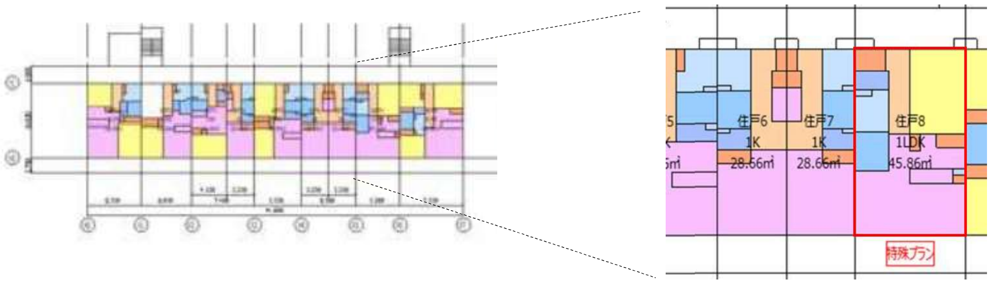


Fig. 8 Study the "group" of domain objects in S1

Study of the overall plan: the span and floor height are arranged and the number of each dwelling unit type and the planned total floor space estimate are calculated.

Study of the dwelling units: the consistency between the overall plan and the dwelling unit plan is checked, and the areas where the standard plan from the client is applied and the areas where a special plan is applied are determined.

2.6. Extension of utilization

Two methods were prepared to objectively assess the examination result from S1. One is landscape simulation, and the other is quantity calculation. Using programming allows for fast verification through both methods.

2.6.1. Landscape simulation

An object "group" that unifies the columns, beams, exterior walls, windows, balconies, exterior corridor, and stairs was prepared. Our research team calls this the "exterior set." In the space volume "group" that was prepared for the overall plan, the vertical objects of each span were arranged horizontally. The method where one model was prepared for each horizontal layer, and these models were layered, was employed. This is owing to the fact that layering horizontal objects vertically is highly suitable for the exterior walls, wherein strong horizontal elements: balcony and exterior corridor exist. The relationship between the interior and the exterior spaces in architecture, where the compositions inside and outside do not necessarily match, is reflected in the production method of the BIM model. This fact also suggests that BIM is not merely a tool.

For the "exterior set," turning the objects based on the BIM categories and the columns, beams, and floor objects into a "model group" when producing a "group" is common. However, as the shape information of objects is different for each category, highly complex programming is required to place these objects in appropriate positions and simultaneously perform parametric transformations according to their spans and floor heights. Therefore, in this study, the "group" objects were prepared by nesting the objects from the most common category, which is called the "common" model in Revit. Rapid transformation using common parameters is possible with object "groups" prepared through nesting.

Producing a BIM model based on the correct categories for S2, which is the next stage, will be necessary. By assigning categories such as columns, beams and floors to each object as its material name, giving each component its category information in preparation for this replacement is possible. Moreover, after setting the shapes in S1, automating the reading of the shape information of each object and its replacement with the correct native object would be possible based on the categories according to the material names only through fairly simple programming. This is a method that prioritizes the way of thinking of a "group" that is not mentioned at all in Revit textbooks, and it can be applied for other purposes as well.

While the usage of an "exterior set" allows for easy manual arrangement according to the space volume groups, even easy automation would be possible using programming. Coordinating with the landscape simulation software "Lumion," which is capable of direct coordination with Revit, after arranging the "exterior set" and the speedy production of photorealistic perspective drawings and movies becomes possible. Moreover, this makes it easy for the client to determine whether the building arrangement and volume are appropriate.

Fig. 9 Exam Simulate the landscape very quickly after setting the spatial volume

2.6.2. Approximate quantity calculation

Perform "material aggregation" based on the "materials" in Revit is possible. By integrating the parameters for obtaining the "capacity" into each component of the "exterior set," obtaining the total estimated value of all the components becomes possible. By setting the average reinforcement ratio of each component, including columns, beams, and floors, estimating the amount of steel reinforcement becomes possible. As adjustments, such as the addition of values the model cannot collect based on empirical values, are made during the estimation, linking the totalization table of Revit to MS Excel will be highly efficient. To further increase the estimation accuracy, one must read the shape information of the exterior set and produce a skeleton model based on the correct Revit native categories. The figure below shows an example of the skeleton model produced through programming. This is, in fact, the skeleton model for S2 and is also a method for smooth transition from S1 to S2, after completing S1.

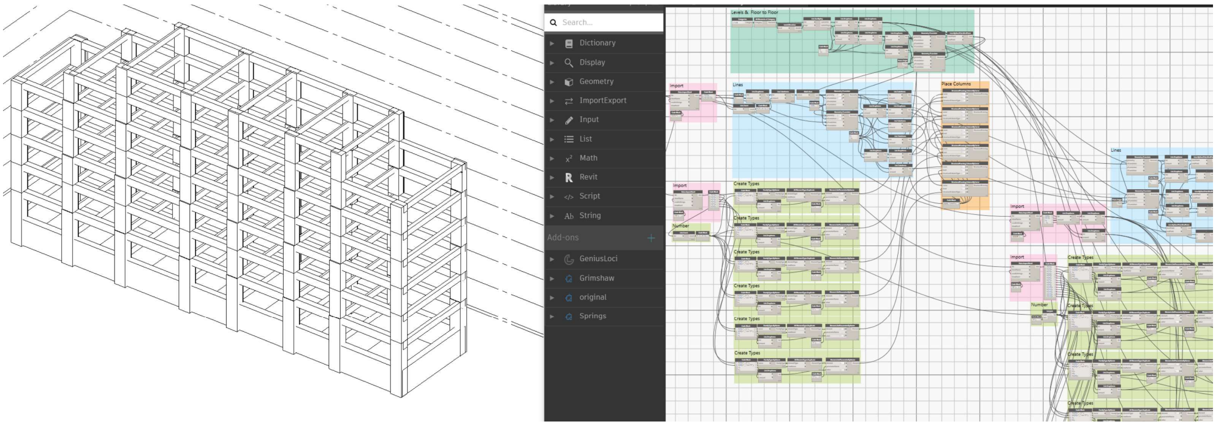


Fig. 10   More accurate approximation. Create S2 Skeleton Model

3. Conclusion

This study demonstrated the effectiveness of the examination process that was identified through the analysis of the apartment design characteristics and the structural characteristics of BIM at the S0 stage and S1 stages. The two types of object groups produced during this research have actually been used by a design team specialized in apartment design to confirm their usability, and their potential for practical application and contribution to the clarification of the examination task at each stage have been confirmed. We expect these two objects to be utilized in specific tasks and to become beneficial to both clients and contractors by improving workflow.

This research is based on the contents of the study of the “(provisional name) collective housing design BIM guideline” jointly developed by Urban Renaissance Agency, Nippon Sekkei Co., Ltd., and Iwamura. express gratitude.

References

[1] Design BIM Workflow Guidelines ver.1 ,kentiku sekkei sankai Japan, (in Japan), 2021

[2] The Daily Engineering & Construction News, (in Japan), “Exchange of opinions with municipal housing construction related organizations”,2022.2.28

[3] IWAMURA Masato, ENDO Kazuyoshi, OKADO Satoshi, “Examination of translation potential between design-oriented BIM and construction-oriented BIM“, 36th Proceedings of Symposium on Building Construction and Management of Projects of AIJ (in Japanese), pp. 239-244, 2021

[4] IWAMURA Masato, ENDO Kazuyoshi, SATOSHI Okado, “Attempts of production design using BIM in construction projects, part 2 Examination of productivity improvement by unitizing BIM objects for design process,” 2021 Summaries of technical papers of annual meeting of AIJ(in Japanese). , pp. 109-110, 2021

[5] DOI Shushi, TAKADA Mitsuo, YASUEDA Hidetoshi, KAMO Midori, “The role of fixed infill when installing and changing variable infill -Through the experiments in “Infill Laboratory Glass Cube” located in Next21-” Transactions of AIJ. Journal of architecture, planning and environmental engineering 78.11 (in Japan), pp. 11-18, 2013, DOI : 10.3130/aija.78.11

[6] OKADO Satoshi, ENDO Kazuyoshi, IWAMURA Masato, “Research on construction period examination at the initial stage of basic design using BIM, 36th Proceedings of Symposium on Building Construction and Management of Projects of AIJ (in Japanese), pp. 233-238, 2021

[7] ENDO Kazuyoshi, IWAMURA Masato, OKADO Satoshi, “Attempts of production design using BIM in construction projects Part 1 Examination of productivity improvement by unitizing building parts and elements,” 2021 Summaries of technical papers of annual meeting of AIJ (in Japanese). , pp. 107-108, 2021

[8] ISHIZU Yuko, “Computational BIM and with Dynamo+Revit,”, 1st printing, Tokyo: Japan, BNN (in Japanese), 2022, ISBN: 978-4-8025-1210-7

PRODUCTION OF BIOMIMETIC STRUCTURES USING VORONOI TESSELLATION AND 3D PRINTING TECHNOLOGY: POSSIBILITIES AND PRACTICAL ISSUES

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Abstract

This paper discusses the development of a new algorithm for determining the internal tissue density of structural members using the finite element method and Voronoi tessellation. The study aimed to reduce the density of structural elements while maintaining their original purpose by filling the interior of the members with interconnected strut members to replicate the structure of animal bones. The strut members were created using the edges of Voronoi cells, and stress was used as an additional variable during the Voronoi iteration to prevent stress concentration on the strut members. The proposed approach resulted in a more uniform stress distribution in the strut member than when Lloyd's algorithm was used. However, perfect uniformity was not achieved due to certain factors, and several issues were identified during the 3D printing process. These findings will refine the proposed algorithm to achieve perfect uniformity of stress distribution in the following steps. The approach presented in this study offers unprecedented opportunities for modern engineering to create structural members that are equally resistant to internal stresses as observed in animal bones.

Keywords: biomimetic structure, Voronoi tessellation, 3d printing.

1. Evolution of Beam Design

The utilization of beams in the construction of bridges and buildings has undergone a considerable transformation throughout history. Initially, beams used in construction were likely made from natural resources, such as wood. However, the enhanced understanding of structural behavior has exposed the inefficiency of using beams with a rectangular cross-section in terms of material utilization [1]. In the 19th century, the introduction of new materials, including steel and concrete, stimulated the development of beams with various cross-sections. Efforts to find structural cross-sections that utilize material more efficiently than rectangular ones followed. This has led to the developing of sections with a high strength-to-weight ratio, such as I-shaped steel wide flange beams and T-shaped concrete beams, that can reduce their weight while maintaining load-bearing capacity [2, 3]. Despite these advancements, the cross-sectional design of mammalian and avian bones, capable of withstanding significant stresses despite their low density, suggests that further improvements to the strength-to-weight ratio of engineering members used in construction projects are possible [4].

Mammalian and avian bones have a unique structural composition supporting relatively high loads while remaining lightweight. The exceptional load-bearing capabilities of these bones can be attributed to the combination of two distinct bone tissues, cortical and cancellous bone. Cortical bone, also called compact bone, forms the outer layer of the bone and is characterized by its high density and strength. This compact outer layer allows the bone to resist bending and torsional forces, thus making it strong and rigid. In contrast, cancellous bone is located within the bone and is characterized by a lattice-like structure. It comprises a network of interconnected struts and bone tissue plates that provide support while minimizing weight. The combination of cortical and cancellous bone tissues creates a structure optimized for strength and weight reduction. Specifically, cortical bone provides an outer shell that resists bending and torsional forces, while cancellous bone provides a load-bearing and weight-reducing internal structure. Moreover, bones can adapt to their environment via a process called remodeling, which involves the reconstruction of bone tissue in response to mechanical stress [5]. Through this process, the cross-sectional area is increased where the stress is concentrated, resulting in the even distribution of load over the entire length of the bone.

2. Biomimicry and 3D Printing

Biomimicry refers to the utilization of nature-inspired designs and solutions for the creation of innovative products. In structural design, biomimicry has gained significant attention as a means to address complex design problems. The application of biomimicry in structural design is exemplified by the utilization of honeycomb structures, as observed in beehives. Such structures consist of hexagonal cells, which offer both high strength and lightness, while also facilitating their production via conventional manufacturing techniques. Honeycomb structures are employed in the design of various structures, including airplane wings, bridges, and other weight-sensitive structural components that demand high strength.

However, traditional manufacturing methods cannot produce structural members that mimic the structure of animal bones, with dense cortical bone on the outside and low-density cancellous bone on the inside, to be strong and lightweight. However, 3D printing technology has recently emerged as a promising method for creating biomimetic structures that imitate living organisms, surpassing the limitations of traditional manufacturing methods. The production of such structures has already been attempted in various fields, such as using coral growth patterns and shell structures to design and print 3D structures for implants [6, 7]. The combination of biomimicry and 3D printing is expected to lead to the development of more robust and lighter members for architectural applications, based on principles observed in nature, such as the structure of bones or the shape of leaves. This will enable a secondary optimization of the structural member that will further increase the strength-to-weight ratio beyond the primary optimization achieved by improving the cross-sectional shape of the member [8].

3. Voronoi Tessellation

The secondary optimization, aimed at reducing weight while maintaining strength, necessitates the development of an internal structure with interconnected struts that provide support while creating voids similar to cancellous bone. Various methods can achieve voids within the structure while also providing stress transmission through an internal structure. One such method is the Voronoi tessellation, a mathematical concept introduced in 1908 by Georgy Voronoi [9]. This approach divides space into multiple cells based on proximity to a set of seed points. The cell is defined such that all points within the cell are closer to that seed point than to any other point in space. Voronoi edges represent the boundary between the cells and are equidistant from the two nearest seed points, which can be used for the creation of unique internal structures with interconnected struts.

The creation of internal structures with interconnected struts utilizing Voronoi tessellation involves the following steps:

1. Space definition: Define the space where interconnected struts will be created.
2. Seed point placement: Place a set of seed points within the defined space. The placement can be random or specific, depending on the desired outcome.
3. Voronoi cell generation: Generate the Voronoi cells for the given space using the seed points as a reference. Each cell is unique to a seed point and contains all points closer to that seed point than any other.
4. Struts creation: The struts illustrated in the following figure can be created using Voronoi edges.

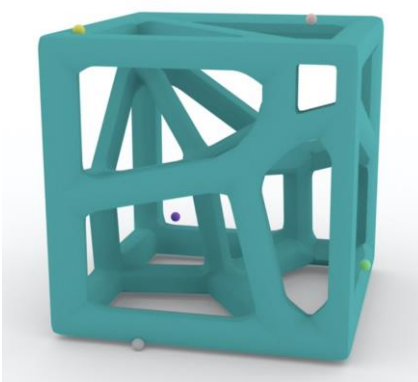

Fig. 1. Example struts created using Voronoi edges

4. Creation of Stress-Weighted Struts using Voronoi Tessellation

When a structural member with a fixed cross-section is used as a beam, it experiences various internal stress concentrations. The concentration of these stresses depends on the pattern or position of external loads applied to the structure. The structure's stability relies on its members' effectiveness in resisting stress in concentrated areas. However, traditional manufacturing methods use the same amount of material throughout the member, resulting in areas with low internal stress being unnecessarily heavy.

The same issue can arise with interconnected struts produced using Voronoi cells. If these struts were created using Voronoi cells evenly distributed throughout the structural member, those located in regions of stress concentration would be subjected to more stress than those in the low-stress areas. This impractical scenario can be resolved by decreasing the size of the Voronoi cell in the stress-concentrated region. As the size of the Voronoi cell decreases, the number and density of Voronoi edges increase, resulting in shorter and more numerous struts produced using them. This method ensures that the struts inside the structure are subjected to equal stresses.

One way to adjust Voronoi edge density is to add more seed points in stress-concentrated areas for Voronoi tessellation. Alternatively, if increasing the number of seed points is not feasible, the seed points from non-stress-concentrated regions can be relocated to the stress-concentrated areas. The following steps describe the process:

1. Seed placement: Place a series of seed points evenly within a defined space.
2. Voronoi cell generation: Generate Voronoi cells for the defined space using the seed points as reference points.
3. Struts creation: Create struts using Voronoi edges generated in the previous step.
4. Stress calculation: Compute the stress on the struts using finite element analysis.
5. Seed points movement: Move seed points towards stress-concentrated regions.
6. Voronoi cell generation: Generate Voronoi cells using the relocated seed points.
7. Iteration of the above process: Repeat this process until the stress on the struts is uniform.

The Lloyd algorithm, also known as Voronoi iteration, is a commonly used technique for determining seed points for Voronoi tessellation in the next generation based on the Voronoi cells of the previous generation [10]. This process involves iteratively refining an initial set of seed points to generate a stable set of Voronoi cells. Initially, the Voronoi diagram is computed for the seed points, and then each seed point is moved to the center of the corresponding Voronoi cell. Next, the Voronoi cells are recalculated using the new set of seed points, and this process is repeated until the Voronoi cells converge to a stable configuration. The Voronoi iteration technique is often employed in computational geometry to create Voronoi diagrams with desired characteristics, such as evenly spaced cells or cells that adhere to specified boundaries.

The paper proposes a Voronoi iteration incorporating the stress applied to the Voronoi edge as an additional variable in the Lloyd algorithm. This modification results in the new center of gravity of the Voronoi cell being a function of both the spread of the cell and its relative weighted stress. The weight can be directly or inversely proportional to the stress generated in the Voronoi cell. When using directly proportional weighting, points inside a Voronoi cell with high stress have a greater impact on the new stress-weighted centroid calculation, while points with low stress contribute less. In each iteration, this process causes the new Voronoi sites to migrate toward high-stress regions. The generalized pseudocode for this technique is presented below.

$\forall \{\mathcal{S}_i\}_1^n \subset B$

Compute the Voronoi Cells C_i

Compute the Voronoi Scaffold

Run Finite Element Analysis

$\forall \{\mathcal{S}_i\}_1^n \subset B$

if $\{p_j\}_1^k \subset C_i$

$$\bar{i} = \frac{\sum_0^k (p_j * w_j)}{\sum_0^k (w_j)}$$

$$\bar{i} \rightarrow i$$

where B is the optimization bound, C_i is the Voronoi cell corresponding to the Voronoi site $\mathcal{S}_i$, p_j are the coordinates of the j^{th} finite element analysis node among k nodes, and s_{p_j} is the von-Mises stress at node p_j. Here, w_j represents the weight associated with stress-weighted centroid computation. As stated earlier, this weight could be directly proportional to the stresses developed, for this investigation was simply equated such that $w_j = s_{p_j}$ and be referred to as Treatment A. The other possibility, where the weight is inversely proportional, was proceeded considering $w_j = \frac{1}{s_{p_j}}$ and is referred to Treatment B for the rest of this text.

5. Evaluation of the Proposed Algorithm

The proposed algorithm was evaluated on a 2.5D MBB steel beam. The material density is set to 7,850 kg/m3, the Young's Modulus is 200 GPa, and the Tensile Yield Strength and Tensile Ultimate Strength are 250 MPa and 460 MPa, respectively. The element size for finite structural analysis is set to 0.5 mm.

The beam is subject to loading and boundary conditions that simulate a simple support beam. The beam has a length of 6L, a thickness of 0.1L, and a height of L, while the dimensions of the support and loading blocks are ΔL x L x 0.1L. The value of L is fixed at 10mm, and ΔL is set to 2mm. A load of 100 N is applied to the top of the beam. The Extrusion Scaffold factor is kept fixed at φ = 0.755, resulting in a porous scaffold volume that is 15 percent of the total volume of the boundary to be optimized, achieving 85 percent porosity. By maintaining the porosity, the overall volume of material remains unchanged, with only the material repositioning based on changes in the Voronoi sites.

The top image of Figure 2 shows the initial Voronoi cells created with 50 randomly positioned seed points and the white-colored strut members resulting from these cells. The bottom image displays the von Mises stress developed on those members. The inner strut members appear thicker than those along the edge because their thickness results from a union of adjacent cells.

The Voronoi cells in Figure 3 underwent 20 iterations of Lloyd's algorithm. Figure 4 shows the resulting distribution of strut members and the corresponding structural performance, which displays a more uniform distribution.

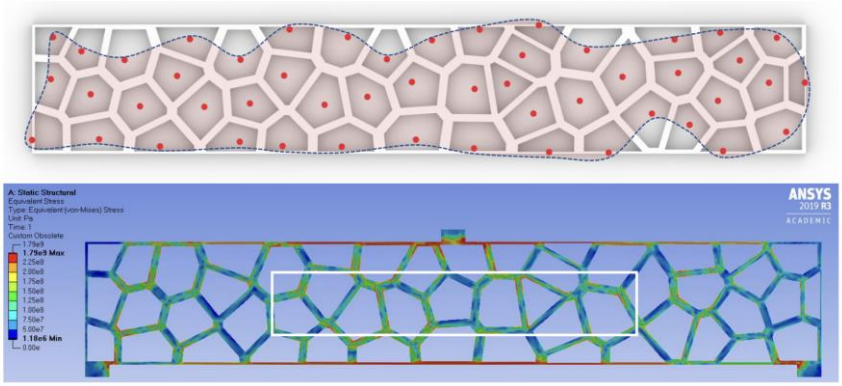

Fig. 2. Initial beam at zero iteration

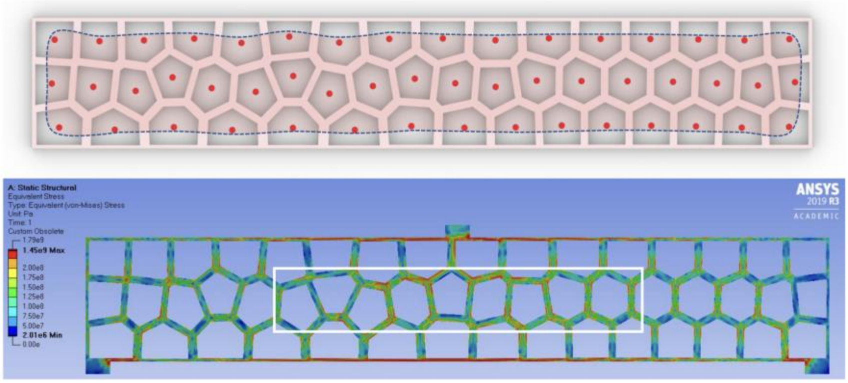

Fig. 3. Beam after 20 iterations with Lloyd's algorithm

Treatment A used weights directly proportional to the stresses developed at the nodes. As a result, the Voronoi sites are positioned closer to the edges with higher stresses, as seen in the top image of Figure 4. Compared to the initial beam in Figure 2 and the control beam in Figure 3, the Voronoi sites are particularly close to the edges in the third middle section, which had high stresses, as indicated by the structural performance in the bottom image. The higher stresses in the centre third of the top and bottom bands may prevent the Voronoi sites from clustering closer together. In contrast, treatment B used weights inversely proportional to the stresses developed at the nodes. As a result, the Voronoi sites appear to have clustered away from the top and bottom edges, as seen in the top image of Figure 5. This is a significant difference from the previous observations. Additionally, the Voronoi sites appear to have clustered in the top left and top right regions, with lower stresses than the surrounding areas.

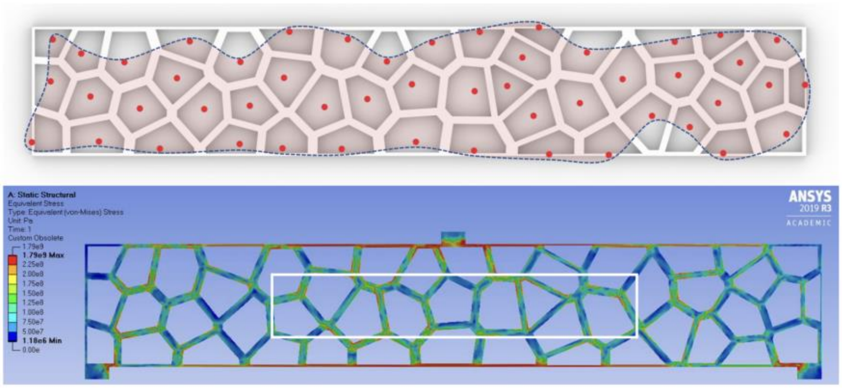

Fig. 4. Beam after 20 iterations with Treatment A

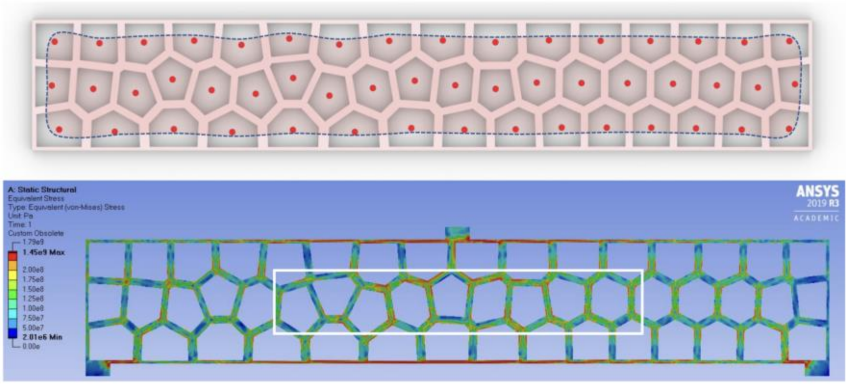

Fig. 5. Beam after 20 iterations with Treatment B

6. Evaluation of the Proposed Algorithm

To identify potential factors affecting the study results, it was essential to produce physical members. This investigation was separated into three distinct categories. The first category involves an algorithm that generates a two-manifold volume using 3D Voronoi tessellation while altering strut thickness and density. The second category involved transforming the geometric model into a format that manufacturing machines could read. Lastly, the third category dealt with manufacturing procedures and conditions.

The proposed algorithm used in this investigation was executed in the Rhinoceros-Grasshopper 3D software. First, to convert the edges of the Voronoi cells into volume entities, a Boolean union operation was performed, and a cylindrical scaffold was created around the edges. The thickness of the resulting struts can be adjusted by changing the radius of the cylinder around them. The second and third categories are contingent on the particular manufacturing method under examination. This study's focus was narrowed to Fused Deposition Modelling (FDM) due to its available capacity and commercial feasibility. FDM involves layer-by-layer deposition of melted thermoplastic onto a build platform, allowing for the versatile use of materials ranging from biodegradable PLA plastic to impact-resistant Kevlar reinforcement. The selection of the FDM 3D printer and the choice of biodegradable Polylactic Acid (PLA) as the single 3D printing material determined the second categorical factor. When selecting parameters, machine capabilities such as nozzle size, temperature, fill pattern and percentage, print speed, and tool head movement were considered. The third category is related to manufacturing factors such as print bed levelling, support-free projection angle range, and production tolerances.

The FDM 3D printer successfully printed the small-sized shapes obtained from the 2.5D Voronoi tessellation. This was followed by the production of the 3D Voronoi tessellation. Figure 6 illustrates irregular modules that formed a modular arch. The density of the Voronoi cells varied based on the location of the Voronoi sites. To test the printer's capability to print different cross-sections, the outer edge of the printed form was made thicker than the inner strut.

The main challenges encountered in creating 3D Voronoi tessellation-based shapes pertain to the design, particularly in geometric modelling parameters. For instance, printing horizontal elements without support is not feasible with a 3D printer, necessitating modifications to the Voronoi tessellation to enable controlled projections without overhangs or supports. Moreover, it is essential to consider the strut joints and print head movement in these areas during the design phase. Another design challenge is to devise an algorithm capable of adjusting post thickness.

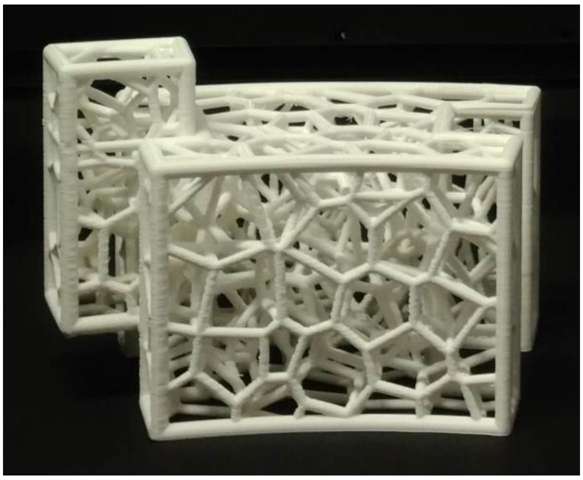

Fig. 6. A 3D module created using Voronoi tessellation

7. Conclusions

This study aimed to reduce the density of structural elements using Voronoi tessellation while maintaining their original purpose. To achieve this, the interior of the members was filled with interconnected strut members to replicate the structure of animal bones. The creation of the strut members was performed using the edges of Voronoi cells. To prevent stress concentration on the strut members, stress was used as an additional variable during the Voronoi iteration. The proposed approach resulted in a more uniform stress distribution in the strut member than when Lloyd's algorithm was used. However, it was found that perfect uniformity was not achieved due to certain factors. Moreover, during the 3D printing process, several issues were identified that need to be addressed to improve the proposed algorithm. These findings will inform the refinement of the proposed algorithm to achieve perfect uniformity of stress distribution in the following steps.

References

[1] G.I.N. Rozvany, M. Zhou, “The Coc Algorithm, Part 1: Cross-Section Optimization of Sizing,” Computer methods in applied mechanics and engineering, 89: 281-308, 1991. https://doi.org/10.1016/0045-7825(91)90045-8.

[2] L. C. Bank, P. J. Bednarczyk, “A Beam Theory for Thin-Walled Composite Beams,” Composites Science and Technology, 32(4):265-277, 1988, doi: 10.1016/0266-3538(88)90065-6.

[3] B. Addis, “The Crystal Palace and Its Place in Structural History,” International Journal of Space Structures, 21(1), 2006, doi: 10.1260/026635106777641199.

[4] T. N. Sullivan, B. Wang, H.D. Espinosa, M.A. Meyers, “Extreme Lightweight Structures: Avian Feathers and Bones,” Materials Today, 20:377-391, 2017, doi: 10.1016/j.mattod.2017.02.004.

[5] T. M. Ryan, A. Walker, “Trabecular Bone Structure in the Humeral and Remoral Heads of Anthropoid Primates,” Anat Rec (Hoboken), 293(4):719-29, 2010, doi: 10.1002/ar.21139

[6] B. Nematollahi, M. Xia, J. Sanjayan, “Current Progress of 3D Concrete Printing Technologies,” In ISARC. Proceedings of the International Symposium on Automation and Robotics in Construction. IAARC Publications, 2017, doi: 10.22260/ISARC2017/0035.

[7] A. Al Rashid, S. A. Khan, S. G. Al-Ghamdi, M. Koc, “Additive manufacturing: Technology, applications, markets, and opportunities for the built environment,” Automation in Construction, 118, 2020, doi: 10.1016/j.autcon.2020.103268.

[8] J. Plocher, A. Panesar, “Review on Design and Structural Optimisation in Additive Manufacturing: Towards Next-Generation Lightweight Structures,” Materials & Design, 183, 2019, doi: 10.1016/j.matdes.2019.108164.

[9] G. Voronoi, “Nouvelles Applications Des Paramètres Continus À La Théorie Des Formes Quadratiques”. Deuxième Mémoire, Recherches Sur Les Parallélloèdres Primitifs. Journal für die reine und angewandte Mathematik, 1908: 198-287, doi: 10.1515/crll.1908.133.97.

[10] S. Lloyd, “Least Suares Quantization in PCM,” IEEE Transactions on information theory, 28(2):129-137, 1982, doi: 10.1109/TIT.1982.1056489.

The Theatre Metaphor for Spatial Computing in Architectural Design

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Abstract

New digital technologies require new conceptual approaches to help potential users understand existing and envision new use cases and applications. Moving from desktop computing to spatial computing (virtual, augmented, mixed and extended reality environments) also requires the introduction of new metaphors. New interaction and visualisation possibilities afforded by current devices are causing virtual and real worlds to merge into an inseparable unity of reality and imagination.

There are many similarities between theatre and AEC workflows. However, the theatre process is scaled down in terms of space, time, and budget, and is therefore better suited to explore innovative and experimental methods. In order to conceptualise the role of a novel spatial computing drawing tool (MR.Sketch) in existing AEC processes, we propose the theatre metaphor, which embeds the conceptual foundations of the tool in a collaborative design workflow based on the cooperation of different domain experts.

The metaphor proposal includes the analysis of the following theatre concepts: integrative collaboration with specialists, stage infrastructure, workshops for different tools and manufacturing methods, stocks and the immersive experience of space and time in different scales. We illustrate the capabilities of the theatre metaphor to cover the entire creation and performance process of architectural design in an experimental mixed reality sketching application. The implementation of an early prototype of the sketching application was used to evaluate the applicability of the theatre metaphor to spatial computing.

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Keywords: computational design tools, early architectural design, sketching, spatial computing, theatre metaphor.

1. From Desktop Computing to Spatial Computing

When Computing became personal, which happened around the 80's in the 20th Century, new forms of interaction were necessary, that allowed people outside the computer engineering community to work with the operating system and applications. Beside voluminous manuals that explained the technical aspects, metaphors were generated to link well understood concepts to digital ones. User interfaces started with pure text layouts and the used metaphors were commands and menus. Menus should remind people of selecting choices in a restaurant. The development of graphical user interfaces popularized the usage of personal computers even more. Windows, the use of the mouse and the desktop were two-dimensional metaphors that were used for several decades until now. Although the first augmented reality device dates back to the 60's, created by Sutherland [1], spatial user interfaces were not feasible at that time, as the computing infrastructure filled an entire room. The creation of virtual and augmented reality devices in the 90's required to think of spatial ideas for user interfaces.

Greenwold described spatial computing as a concept to integrate physical space into digital environments [2], where computing depends strongly on spatial parameters and spatial events, differing from computing of spatial data as in classical geographic information systems (GIS) or in building information models (BIM). Spatial computing thus requires mobile devices to be able to interact with space, such as tablets, smart phones, and wearable devices, like smart glasses (see Figure 1).

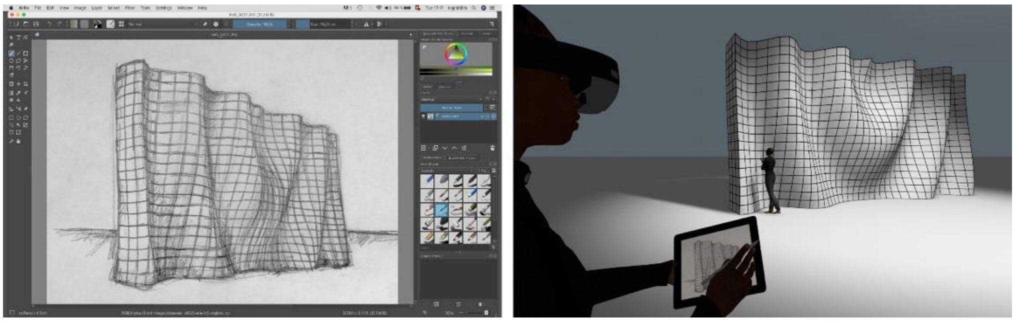

Fig. 1. Desktop computing (Krita [3]) vs spatial computing (Concept visualisation of MR.Sketch)

Beside mobile and wearable devices, other technologies are increasingly enabling spatial computing as computing gets integrated into almost any object, that surrounds us. Smart artificial actors like robots, drones and autonomous vehicles become part of our daily life, also outside industrial applications. We thus see mixed reality spatial computing as an ongoing trend with increasing importance.

2. Spatial Metaphors in Computing

Spatial Computing needs Metaphors that relate to well known spatial concepts with user interaction. In the digital spatial domain that ranges from virtual to mixed and to augmented spaces, several metaphors have been used, mostly for information visualization or for virtual reality environments. The landscape metaphor was used by Schreiber and Misiak [4] to visualize software architecture as islands in the sea. Several use-cases for landscapes in information visualization are demonstrated by Fabrikant et al. [5]. An overview of several applications of the city as a metaphor to visualize software is described by Jeffery [6]. A strategy for collaboration in virtual reality was created using analogies from the building site [7]. Many spatial metaphors refer to single rooms like the apartment [8], the curiosity cabinet [9] and the Studierstube [10], [11]. The Holodeck, a concept from the science fiction series "Star Trek" became an often-used metaphor in virtual reality computing, examples are presented by Kymalainen [12] and Raybourn et al. [13].

Laurel made the theatre metaphor for user interface design popular [14], her main ideas were to enable different actors and interactive actions focused around the stage, typically from a proscenium theatre. Her concepts were not focused on the stage as spatial metaphor, as her work appeared first in the 90's and spatial computing was not an issue at that time.

The theatre metaphor influenced others, like in cartography [15] or in a more general work about the narrative in digital media [16]. Even before Laurel, Gould [17] described how programming by rehearsal could help non-programmers to develop software visually.

3. The Extended Theatre Metaphor

3.1. Concepts from Theatre

Theatre is a total work of art, a Gesamtkunstwerk. The notion describes theatre, in particular opera, as an interplay of different arts, including architecture, sculpture, painting, literature, music, and dance. The total work of art not only comprises different arts, but also their perceptibility with different senses.

Theatre is the interaction of the most diverse approaches, art genres, artistic means of expression and practices. Specialists from a wide range of fields contribute their skills. From the very beginning of the project, through all stages of development, a theatre production is characterized by the collaboration and integration of all contributors. The director, choreographer, dramaturge, set designer, costume designer and musical director come together in the preparation phase. Experts from different disciplines are consulted for advice in the early phases of design. Professionals of the most diverse directions work on the execution of the project. Specialists from various disciplines, such as performing arts, visual arts, music, dance, and martial arts, as well as experts and craftsmen of all kinds are involved in a theatre production. Theatre provides a variety of workshops. Every larger theatre has a metal and carpentry workshop, sculptor's studio, decorator, paint shop, department for tailoring and dressmaking, and workshops for making masks and wigs. Stocks with ready-mades, such as set elements and backdrops, furniture, props, and costumes are available. These objects serve as proxy objects for the rehearsal, can be adapted if necessary or used as they are in the performance.

The workflow of a theatre production is comparable to any other creative process and can be divided into preparation, design, and realization. The place where theatre happens is the stage. Scenography, stage design, describes the design of the scene. The scene is the actual heart of the theater. The word scene can mean either "place" or "part of an action" that happens in that place. The notion has therefore both spatial and temporal connotations. Scenography can be the design of spaces as well as the design of temporal processes. All performances require preparations and sometimes extensive rehearsals. Rehearsal is a special feature of the creation process at the theatre. Test rooms are built, and mock-ups and rehearsal decorations are produced in original scale. Fischer-Lichte defines staging as the process of planning, testing, and determining strategies, which aim in bringing forth the performance's materiality [18]. Staging is an intention, it is future-oriented, determined, operative, reproducible and can be fixed in a script or a scenario (see Figure 4).

Fig. 4. Sketch, Model, Rehearsal, Performance, *Idomeneo*, Vienna, 2017, © A. Bardel, M. Buechling

What all concepts from the field of entertainment, gaming industry and indeed theatre have in common is that they offer the opportunity to try out something new and at the same time create the protected space to do so.

3.2. The Relationship between Theatre and Architectural Design

Scenography is a conceptual tool for creating fictional environments. Although scenography was so far mainly associated with theatre aesthetics, exhibitions, or any other form of staging in the world of entertainment industry it is now increasingly being used in architecture, as demonstrated in [19]. Scenography is a spatial art where various artistic disciplines combine to create an immersive spatial experience. Introducing scenography into the field of architecture also means understanding architecture as an art, the art of building. The creation process in architectural design is comparable to the development process of the theatre production. The design is developed in collaboration with various experts. However, it would be desirable if the integration of specialists also took place in the early design phases, the phases that are actually crucial for the development of the design. In architecture as well as in stage design, the design is determined by numerous specifications, requirements, and constraints. In contrast to theatre, with its great artistic freedom, the design and implementation of a project in architecture is bound to a strict framework of building regulations and procurement procedures. In both disciplines, the project is sketched in experimental early design phases, revised, and further developed in several steps and finally realized. One of the most important differences between theatre and architecture in the development process is rehearsal. Testing the design of a building, practicing the use of architecture could be a decisive innovation in architectural design. Simulation in different areas, such as static calculations or lighting design, could be used in architecture as a substitute for what rehearsal means in theatre.

3.3. Theatre Concepts and Spatial Computing

To use the extended theatre metaphor for user interface design in a mixed reality spatial computing environment we will apply several conceptual mappings, that link the theatre domain to virtual environments. The creation of any virtual world, e.g., game worlds or architectural design environments, requires various specialists with different artistic and technical expertise like writers, modeling specialists, texture painters, software developers, sound designers, etc., thus also creating a total work of art. Technologically, multiple senses must be considered, like visual, auditive and haptic. The creation process of a theatre production can also be mapped to the design of virtual worlds. The integration of specialists demands a digital multi-user environment, which might consist of different views, tools, and corresponding mappings of the real environment to a virtual environment. Simulations, that link the simulation domain to the design domain, preferably in real-time, would greatly enhance the design, allowing rehearsal phases to be applied in the design development. In any creation process, the use of stocks of previously designed objects, play an important role, as with digital assets and software libraries. As virtual worlds take place in a spatial and temporal framework, scenographic strategies need to be linked to virtual concepts, like digital storyboards, semantic descriptions of spaces and activities. Limited space, through the stage dimensions, and limited time, through the length of a play require spatial and temporal scaling, also needed to map any virtual environment to a physical surrounding. The dualism of stage and auditorium, as well as the creation process of a production and its performance can be transferred to any development process and the use of a virtual environment. As theatre can provide a test environment for architecture, it can play a similar role in testing virtual worlds in a mixed reality surrounding, needed to develop new artistic and technological strategies.

4. Developing a Mixed Reality Sketching Application for Architectural Design

The following part describes the development of a mixed reality sketching application as part of a larger research project about advanced computational design (ACD). ACD consists of several sub-projects in the areas of design methodology, visual and haptic design interaction and form finding. The sketching application targets the early phases of architectural design and integrates several computational tools that will allow design evaluation in a much earlier phase than possible before.

4.1. Sketching Strategies

Sketching is mostly seen as the preliminary step of drawing. But sketching is more than just a tool for the first visualization of the design. By combining reality and imagination in a continuous creative dialogue, sketching reveals the intrinsic meaning of an idea (see Figure 5). The first approach to sketching is the connotation with scribbling and doodling. In its development from doodle to design, sketching can be interpreted as form finding. Sketching can also be a systematic strategy of design. From point and line to plane and volume means to characterize sketching as a structured method or a methodology. However, sketching is more than a means of expression. It is also a selection procedure. Sketching means making decisions. Every point, every line, every object, every situation, is a choice.

Sketching is the art of omission. One of the most important aspects of sketching is probably the duality of fact and fiction. Every idea can cause reality, and every existing part of this world can cause a new idea. Sketching is an inner dialogue of what is real and what would be possible. In this sense, sketching can become a tool for thinking.

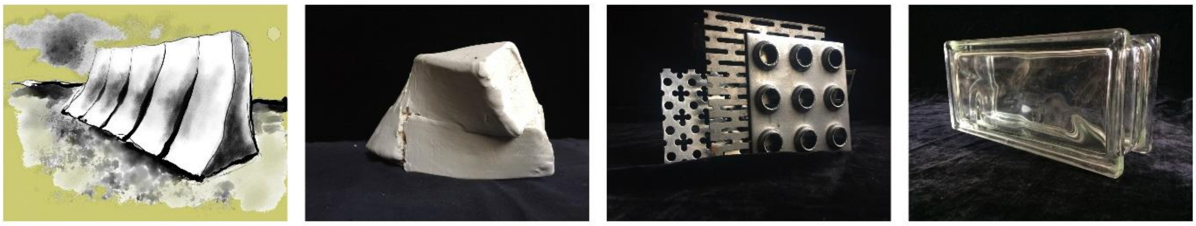

Fig. 5. Sketching a wall: Drawing and painting, Sculpting, Collage, Ready-made

4.2. Digital Sketching in Three Dimensions

Digital sketching in two dimensions (2D), simulating pen and paper, is available in multiple commercial and open-source applications. To be able to sketch in three dimensions (3D) is an ongoing research topic, as there are still several difficulties to solve. Some of the research questions in that areas are: How to use 2D input devices for 3D sketches? How to create direct 3D input? How to create sketches with a context of real objects?

To use current available 2D input devices, like tablet and pen, several approaches create canvas in 3D, e.g. planes or curved surfaces and project 2D strokes onto 3D canvas [20]–[22]. As tablets are used in many cases for 2D input, some approaches track the location and orientation of the tablet to generate 3D canvas [23]. The use of hand gestures was used to create 3D canvas from the hand movement, while using a tablet to create sketches projected onto the canvas [24].

Google Tiltbrush [25] became well known of painting in virtual reality (VR) with inputs from VR controllers, that can track movements in 3D directly. An overview of several painting applications in VR is given by Ramsier [26]. As was shown by Arora et al. [27], a challenge for precise drawing in 3D is the lack of haptic feedback. Müller et al. address this issue by using a Phantom device [28].

Some examples of sketching within a context by augmented reality (AR) techniques are provided by Yee et al. [29], Bergig et al. [30], Paczkowski et al. [31] and Wacker et al. [32].

4.3. A Mixed Reality Prototype

To evaluate the theoretical concepts in practical experiments, we implemented several iterations of a sketching application prototype. We chose the Unity game engine [33] as platform for implementation, as it allows for rapid prototyping by providing built-in functionality in areas outside our scope such as rendering, input handling and cross-platform targeting. The application was designed to provide the following key features:

- Mobility: The target platforms are tablet devices with stylus input to retain the immediacy of sketching.
- Collaboration: Multiple artists and specialists can work simultaneously, but independently on the same project. Additionally, it is possible to exchange data with other applications in real-time.
- Mixed Reality Interaction: The virtual space of the application is strongly connected to the real surroundings of the artist. Navigating the virtual space of the sketch is possible via moving around in real space. Real physical objects can be used to create and manipulate drawing elements.

The following sections describe the specifics of how concepts from the theatre have been realized as functionality in the application prototype.

4.3.1. Stage and Light Infrastructure

The stage serves as the anchor point of the drawing in the virtual 3D space. It provides the bounds and the landmarks for navigation and a sense of scale for the drawing. The aforementioned mixed reality spatial navigation mode works by tracking the position and orientation of the tablet device and use it as a window into the virtual environment. Beside this mode, the application also allows to navigate the virtual space via touch gesture control. As described above, bridging the 2D→3D input problem in an intuitive way with a single viewport is non-trivial. For the touch gesture control in particular, the stage is a key component of efficient and precise spatial navigation and positioning. The landmarks of the stage provide a framing, lowering the time and cognitive effort expended on finding the specific pose in 3D space from where newly sketched lines connect to the drawing in the desired manner.

In the context of spatial navigation, the stage can also be used to register the virtual space to the real physical space around the artist. The application prototype also allows to scale the virtual space and the drawing independently from one another and from the size of the physical space. This functionality is utilized for collaborative work as well, where different artists can observe the drawing from different scales: As one artist sketches on blueprint scale, the other one can traverse the sketched architecture at a real-world scale.

To selectively combine parts of a sketch, 2D drawing applications use the metaphor of layers. Since layering in this manner does not make sense in 3D space, we propose the concept of the fly loft for this purpose. Closely related to the spatial concept of a stage, the fly loft allows to combine partial sketches by raising and lowering the flies they are affixed to. The prototype allows to target and control specific flies to experiment with different combination of forms.

The concept of staging is also implemented as a functionality. The prototype allows for activating a "revolving stage", a smooth animated rotation of the 3D sketch around the center of the stage. This motion is independent from the spatial navigation. Staging the artwork in such a manner facilitates the sense of structure and dimension and aides the process of form finding. To further this, the application also features a mixed reality mode that allows augmenting markers with computer generated imagery. The prototype utilizes image tracking to import and scale previously saved sketches and anchor them to printed-out markers. Artists can use physical objects for comparison or framing to evaluate their design created in the application (see Figure 6.).

Working with lights is closely connected to this topic as well. MR.Sketch allows the artist to control different aspects of the lighting infrastructure. Directional light and constrained, parametric light fixtures (pars, spotlights) can be activated. Furthermore, it is possible to import photometric data for use in lighting setups in the application. Refer to Figure 7. for a comparison of the rendering visuals. However, lighting simulation is a vastly more complicated task, demanding specialist domain knowledge to meet the requirements of architectural design as well as the needs and ideas of the client (e.g., atmospheres). For a description of our approach to domain knowledge synthesis in the application, refer to Section 4.3.3.

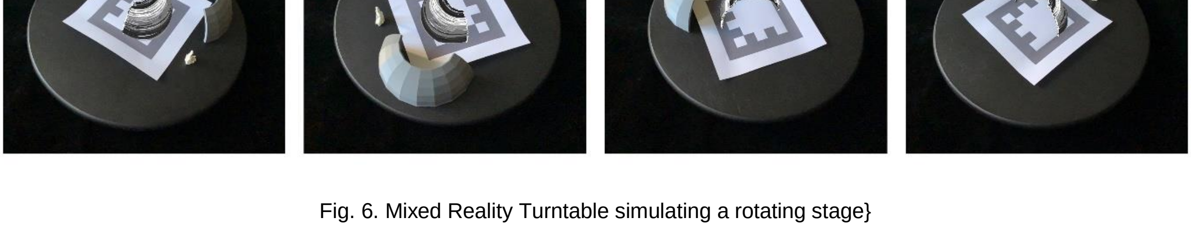

Fig. 6. Mixed Reality Turntable simulating a rotating stage}

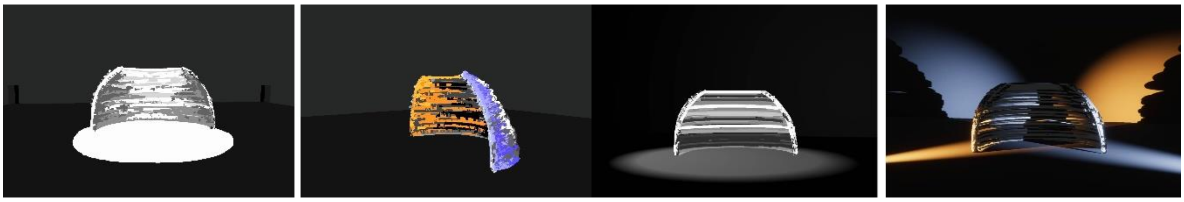

Fig. 7. Left: Sketched light situations, Right: Simplified rendering vs. High definition rendering

4.3.2. Stocks: Physical and Virtual Ready-Mades

Another key strategy in aiding the process of sketching into 3D space via a 2D input surface is also closely related to concepts from the theatre. The concept of stocks, meaning collections of reusables, organized and catalogued ready-mades, translates well to the approach of constructing complex structure from pre-defined shapes during the process of form finding. The prototype realizes this concept with two features: The use of virtual and of physical ready-mades.

To make use of physical ready-mades, MR.Sketch allows artists to instantly create a mesh representation of the physical object inside the virtual space of the sketch. The current target device of the application is an Apple iPad Pro 2020, featuring spatial meshing capabilities via a built-in lidar depth mapping sensor. The prototype utilizes this capability to create a virtual representation of the physical object, which then can be used as drawing canvas. Figure 8. depicts the scanning of a seat and it's use as drawing canvas.

The prototype also enables artists to browse through stocks of virtual ready-mades, different 3D models imported from other modeling and miscellaneous content creation applications. After selecting an object, it is possible to use the 3D mesh as virtual canvas to reuse parts of their shapes, akin to the physical stocks. Figure 8. demonstrates this as well.

Fig. 8. Physical and virtual stocks: Using objects from stocks as drawing guides, Left: Scanning a physical seat and using it as virtual canvas, Right: Similar type of chair from the virtual stocks (Model by K. Albayrak [34])

4.3.3. Integrative Collaboration with Specialists

As in theatre production where many experts in different disciplines come together to develop a scenography and provide feedback for the production team, the designer needs feedback from specialists, often generating complex simulations to evaluate a specific sub-goal. We translate this aspect to a specialized organization of creation tools in the sketching application prototype, apart from a collection of "belt tools" (e.g., pencil, measuring tape, colour palette), tool sets and actions are organized in ateliers. Ateliers have their own workflow specific to the task to perform and provide interaction modalities to aid this workflow.

Further expanding upon this notion, the application is set up in a way to integrate other domain-specific software though these ateliers to improve the decision making in the design process. We aim at providing real-time feedback even in the early phases of design, during the sketching of ideas, where not every part is completely specified. The prototype facilitates integrating other software created by our research partners, such as simulations of different material properties, lighting, panelling or foldable structures.

At this point in the development progress, two approaches have been implemented. One approach enables the integration of our sketching application with the 3D modelling software Rhino [35], more specifically with its parametric, visual scripting environment called Grasshopper. The ACD Sub-Project researching "Flexible Quad-Surfaces for Transformable Design" provided the Grasshopper plugin “Scutes” [36] that generates a parametric flexible surface of revolution. The prototype provides the option to sketch the input (the profile curve for a surface of revolution) for this script, which is packed and sent via network connection to a Rhino.Compute instance. This allows accessing the Rhino and Grasshopper SDKs through a stateless REST API running on Windows Servers [37], and provides the generated mesh in response. The generated mesh is inserted and visualized in MR.Sketch. Figure 9. showcases a sketched surface which provides input elements for the script and a visualization of the resulting parametric mesh in Rhino.

The atelier for lighting design contains tools to facilitate integration with our partner at the ACD Sub-Project "Researching Lighting Simulation for Architectural Design". The prototype lighting tools consist of paint-able light and shadow areas, that can be sketched like the basic lines of the drawing, but instead of positioned freely in space, the lights and shadows can be layered onto previously sketched surfaces. Sketched geometry and painted light/shadow are exported via the glTF format from the prototype. From this data, the lighting simulation specialist's software calculates possible light placement combinations that would approximate the sketched lighting conditions within a given set of constraints. (Light fixture types, placement positions, etc.) Figure 7. illustrates different sketched light situations.

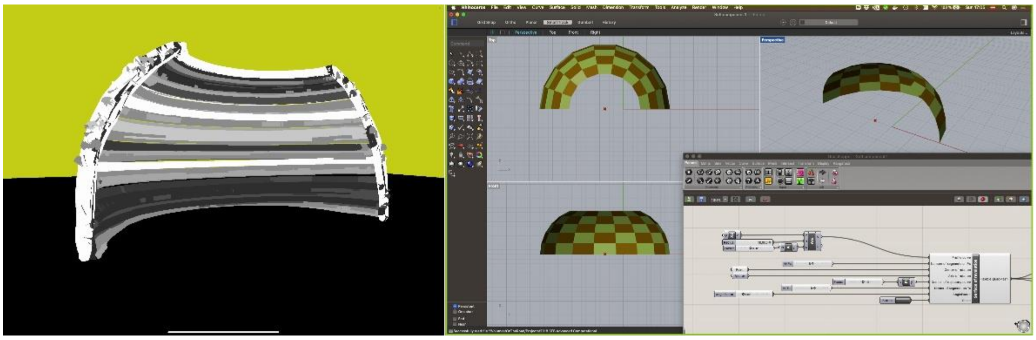

Fig. 9. Integrative Collaboration with Specialists: Parametric Objects in the Sketching Application

5. Conclusion and Future Work

We described an extended version of the theatre metaphor, that includes the creation process of a theatre production as well. After relating the creation process of the theatre to the development process of architectural design, we transferred selected theatre concepts (total work of art, integrating specialists, staging, rehearsal and stocks) to the field of spatial computing. The implementation of the theatre metaphor by means of a mixed reality sketching application makes spatial computing a suitable environment for experiments and innovation and can be applied in architectural design as well as in other disciplines. We described practical applications of these ideas via selected experimental features of a prototype (MR.Sketch).

Future work will expand upon the theatre metaphor by further transfer experiments. We intend to translate the concept of interpretation as a layer of semantic attributes to sketches and the perceived physical environment in our mixed reality application. We will implement expert collaboration as the integration of domain knowledge about architectural design, by utilizing machine learning. For data exchange, a general database of material properties, that fulfill several requirements, like mechanical, optical, and haptic behaviour needs to be incorporated into the application. Through adding audio interfaces and by integrating large-scale haptic feedback our mixed reality sketching application will be extended to other senses, that might be useful for improving user experience and finally architectural design.

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References

[1] I. E. Sutherland, “The ultimate display,” in *Proceedings of the IFIP Congress*, New York, 1965, pp. 506–508.
[2] S. Greenwold, “Spatial computing,” *Massachusetts Institute of Technology, Master*, 2003.
[3] K. Foundation, “Krita Desktop,” *Krita*. https://krita.org/en/download/krita-desktop/ (accessed Apr. 12, 2023).
[4] A. Schreiber and M. Misiak, “Visualizing software architectures in virtual reality with an island metaphor,” in *Virtual, Augmented and Mixed Reality: Interaction, Navigation, Visualization, Embodiment, and Simulation: 10th International Conference, VAMR 2018, Held as Part of HCI International 2018, Las Vegas, NV, USA, July 15-20, 2018, Proceedings, Part I 10*, Springer, 2018, pp. 168–182. doi: 10.1007/978-3-319-91581-4_13.
[5] S. I. Fabrikant, D. R. Montello, and D. M. Mark, “The natural landscape metaphor in information visualization: The role of commonsense geomorphology,” *Journal of the American Society for Information Science and Technology*, vol. 61, no. 2, pp. 253–270, 2010, doi: 10.1002/asi.21227.
[6] C. Jeffery, “The City Metaphor in Software Visualization,” Jan. 2019. doi: 10.24132/CSRN.2019.2901.1.18.
[7] C. Toinard, N. Chevassus, and A. Sgambato, “Collaborative Virtual Reality and the Distributed Building Site Metaphor,” in *WSCG*, 1999, pp. 111–117.
[8] M. Speicher, P. Hell, F. Daiber, A. Simeone, and A. Krüger, “A virtual reality shopping experience using the apartment metaphor,” in *Proceedings of the 2018 International Conference on Advanced Visual Interfaces*, 2018, pp. 1–9. doi: 10.1145/3206505.3206518.
[9] P. Charlton *et al.*, “Use of the Curiosity Cabinet metaphor to support inclusive learning,” in *Proceedings of the 7th International Conference on Software Development and Technologies for Enhancing Accessibility and Fighting Info-exclusion*, 2016, pp. 309–314. doi: 10.1145/3019943.3019988.
[10] D. Schmalstieg *et al.*, “The studierstube augmented reality project,” *Presence: Teleoperators & Virtual Environments*, vol. 11, no. 1, pp. 33–54, 2002.
[11] H. Kaufmann and D. Schmalstieg, “Mathematics and geometry education with collaborative augmented reality,” in *ACM SIGGRAPH 2002 conference abstracts and applications*, in SIGGRAPH ’02. New York, NY, USA: Association for Computing Machinery, Jul. 2002, pp. 37–41. doi: 10.1145/1242073.1242086.
[12] T. Kymäläinen, “An Educational Glance into the Future: Holodeck as a Future Enacted Narrative Learning Technology,” *Journal of Universal Computer Science*, vol. 25, no. 5, pp. 446–464, 2019. doi: 10.1007/978-3-030-21607-8_12
[13] E. M. Raybourn, W. A. Stubblefield, M. Trumbo, A. Jones, J. Whetzel, and N. Fabian, “Information design for xr immersive environments: Challenges and opportunities,” in *Virtual, Augmented and Mixed Reality. Multimodal Interaction: 11th International Conference, VAMR 2019, Held as Part of the 21st HCI International Conference, HCII 2019, Orlando, FL, USA, July 26–31, 2019, Proceedings, Part I 21*, Springer, 2019, pp. 153–164. doi: 10.1007/978-3-030-21607-8_12
[14] B. Laurel, *Computers as theatre*. Addison-Wesley, 2013.
[15] W. Cartwright, “Applying the theatre metaphor to integrated media for depicting geography,” *The Cartographic Journal*, vol. 46, no. 1, pp. 24–35, 2009. doi: 10.1179/000870409X415561
[16] M.-L. Ryan, “Beyond myth and metaphor: Narrative in digital media,” *Poetics Today*, vol. 23, no. 4, pp. 581–609, 2002. doi: 10.1215/03335372-23-4-581
[17] “Xerox Corp: Programming by Rehearsal – ACM SIGGRAPH ART SHOW ARCHIVES.” https://digitalartarchive.siggraph.org/artwork/xerox-corp-programming-by-rehearsal/ (accessed Apr. 11, 2023).
[18] E. Fischer-Lichte, *The transformative power of performance: a new aesthetics*. Routledge, 2008.
[19] U. Brückner, *Scenography: Staging the space*. Birkhäuser Verlag GmbH, part of Walter de Gruyter GmbH, 2019.
[20] J. Dorsey, S. Xu, G. Smedresman, H. Rushmeier, and L. Mcmillan, “The Mental Canvas: A Tool for Conceptual Architectural Design and Analysis,” Oct. 2007, pp. 201–210. doi: 10.1109/PG.2007.64.
[21] Y. Zheng, H. Liu, J. Dorsey, and N. J. Mitra, “SmartCanvas: Context-inferred Interpretation of Sketches for Preparatory Design Studies,” *Computer Graphics Forum*, vol. 35, no. 2, Art. no. 2, 2016, doi: 10.1111/cgf.12809.
[22] M. D. B. Machuca, P. Asente, W. Stuerzlinger, J. Lu, and B. Kim, “Multiplanes: Assisted Freehand VR Sketching,” in *Proceedings of the 2018 ACM Symposium on Spatial User Interaction*, in SUI ’18. New York, NY, USA: Association for Computing Machinery, Oct. 2018, pp. 36–47. doi: 10.1145/3267782.3267786.
[23] T. Drey, J. Gugenheimer, J. Karlbauer, M. Milo, and E. Rukzio, “VRSketchIn: Exploring the Design Space of Pen and Tablet Interaction for 3D Sketching in Virtual Reality,” in *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*, in CHI ’20. New York, NY, USA: Association for Computing Machinery, Apr. 2020, pp. 1–14. doi: 10.1145/3313831.3376628.
[24] Y. Kim, S.-G. An, J. H. Lee, and S.-H. Bae, “Agile 3D Sketching with Air Scaffolding,” in *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*, in CHI ’18. New York, NY, USA: Association for Computing Machinery, Apr. 2018, pp. 1–12. doi: 10.1145/3173574.3173812.
[25] “Tilt Brush by Google.” https://www.tiltbrush.com/ (accessed Apr. 12, 2023).
[26] L. Ramsier, “Evaluating the Usability and User Experience of a Virtual Reality Painting Application.,” 2019. doi: 10.17615/s9z1-m163

[27] R. Arora, R. H. Kazi, F. Anderson, T. Grossman, K. Singh, and G. W. Fitzmaurice, “Experimental Evaluation of Sketching on Surfaces in VR.,” in *CHI*, 2017, pp. 5643–5654. doi: 10.1145/3025453.3025474
[28] F. Müller, M. Pache, and U. Lindemann, “Digital free-hand sketching in 3D-a tool for early design phases,” in *DS 31: Proceedings of ICED 03, the 14th International Conference on Engineering Design, Stockholm*, 2003, pp. 129–130.
[29] B. Yee, Y. Ning, and H. Lipson, “Augmented reality in-situ 3D sketching of physical objects,” in *Intelligent UI workshop on sketch recognition*, Citeseer, 2009.
[30] O. Bergig, N. Hagbi, J. El-Sana, and M. Billinghurst, “In-place 3D sketching for authoring and augmenting mechanical systems,” in *2009 8th IEEE International Symposium on Mixed and Augmented Reality*, Oct. 2009, pp. 87–94. doi: 10.1109/ISMAR.2009.5336490.
[31] P. Paczkowski, M. H. Kim, Y. Morvan, J. Dorsey, H. E. Rushmeier, and C. O’Sullivan, “Insitu: sketching architectural designs in context.,” *ACM Trans. Graph.*, vol. 30, no. 6, Art. no. 6, 2011. doi: 10.1145/2024156.2024216
[32] P. Wacker, A. Wagner, S. Voelker, and J. Borchers, “Physical Guides: An Analysis of 3D Sketching Performance on Physical Objects in Augmented Reality,” in *Proceedings of the 2018 ACM Symposium on Spatial User Interaction*, in SUI ’18. New York, NY, USA: Association for Computing Machinery, Oct. 2018, pp. 25–35. doi: 10.1145/3267782.3267788.
[33] “Unity Real-Time Development Platform | 3D, 2D, VR & AR Engine,” *Unity*. https://unity.com (accessed Apr. 12, 2023).
[34] “LC2 Sofa and Arm Chair | 3D CAD Model Library | GrabCAD.” https://grabcad.com/library/lc2-sofa-and-arm-chair-1 (accessed Apr. 12, 2023).
[35] R. M. & Associates, “Rhinoceros 3D,” *www.rhino3d.com*. https://www.rhino3d.com/ (accessed Apr. 12, 2023).
[36] K. Sharifmoghaddam, G. Nawratil, A. Rasoulzadeh, and J. Tervooren, “Using flexible trapezoidal quad-surfaces for transformable design,” *Proceedings of IASS Annual Symposia*, vol. 2020, no. 28, pp. 1–13, Jun. 2020.
[37] “Rhino Compute Server.” Robert McNeel & Associates, Mar. 30, 2023. Accessed: Apr. 12, 2023. [Online]. Available: https://github.com/mcneel/compute.rhino3d

COLLABORATIVE VIRTUAL REALITY IN CONSTRUCTION

COMPARATIVE STUDY OF TWO REMOTE MULTI-USER SYSTEMS

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Abstract

Ineffective collaboration and communication between the stakeholders of a construction project are one of the most difficult problems to solve in the AEC industry. The rapid development of new technologies has reformed the construction industry in recent years. Indeed, adopting BIM technology and its dimensions improves the collaboration process. The integration of emerging technologies such as virtual reality (VR) based on a BIM model is a potential solution to optimize communication. However, most of the studies on virtual reality and its applications in the construction industry have so far focused on the single-user experience which does not support collaboration and interaction between construction project teams. Multi-user remote virtual reality can offer a solution to the problems mentioned above. Several tools have been developed in other fields such as the video game industry, but their applicability in the construction industry has not been evaluated in the literature. Our research aims to compare two remote multi-user virtual reality support systems to characterize their potential use in the construction industry with BIM models. We then performed a demonstration in the form of two fictitious scenarios to evaluate the proposed tools. This allowed us to identify the potential benefits of the two remote multi-user VR systems to support collaboration and to identify limitations and future improvements. While both systems offer interesting remote multi-user functionality, the Vizard multi-user application can only work over a local area network, which is a major limitation to remote user collaboration. In addition to the features common to both systems, Photon Unity Networking (PUN) offers the ability to communicate with voice in real time.

Peer review under the responsibility of the scientific committee of the Creative Construction Conference 2023.

Keywords: Remote multi-user virtual reality, BIM, remote collaboration, Unity game engine, Vizard, Photon Unity Networking

1. Introduction

The construction industry is one of the pillars of the Canadian economy. However, it has been lagging for years in terms of productivity and performance compared to other industrial sectors because of the great technological, technological, and organizational fragmentation among the team members of a construction project [1,2].

Many people in the sector admit that this gap can be bridged through the adoption of new information technologies such as building information modeling (BIM) Building Information Modelling (BIM) and virtual reality (VR) [2]. Building information modeling (BIM) is the keystone of the fourth industrial revolution in construction, also called construction 4.0. This technology allows the digitization and virtualization of the built environment. In addition, it is a tool that facilitates decision-making during the entire life cycle of a construction project [2]. However, there are some relevant avenues such as the use of the principle of virtual reality. Indeed, several researchers have studied the use of this technology in the construction industry, but it is rare to see solutions based on multi-user virtual reality at a distance multi-user virtual reality-based solutions to support collaboration, communication, and communication and support for constructability analysis meetings. Typically, VR applications are limited to a single user. The diversified geolocation of a construction project's stakeholders is common in the construction industry. Bringing together people who are in an immersive environment will be a potential solution to facilitate communication and collaboration.

Thus, this study proposes a comparison between two remote multi-user virtual reality support systems, to characterize their potential use in construction with BIM models. This paper is composed of four sections. The first section is the literature review. It presents a review of previous scientific studies related to our topic. The second section presents the methodology of the research. The third section presents a comparative study of the two remote multi-user virtual reality tools. The report ends with a section that presents a demonstration of two hypothetical scenarios to evaluate the usefulness of the two proposed tools in the construction industry.

2. Literature review

In recent years, the construction industry has undergone a radical digital transition. Many companies have adopted several technological tools to improve collaboration and productivity. Our literature review will focus on virtual reality, remote multi-user virtual reality, its characteristics, and its applications in the construction industry. Then, we will focus on the scientific studies concerning multi-user virtual reality in construction.

2.1. Multi-user virtual reality

Collaborative virtual reality is a shared virtual environment designed to support collaborative activities. It is an extension of single-user virtual reality. This technology allows participants to share the same virtual environment to achieve a common goal. Indeed, collaborative virtual reality offers an infinite graphical digital landscape allowing multiple users to interact with each other. The representations of individuals or data can be in the form of an advanced 3D graphical representation, 2D representations, or simply text pasted on a plane [3]. The video game industry and the training of military and industrial teams are the main application areas of collaborative virtual reality [4]. Collaborative VR systems proposed in the AEC industry are usually CAVE-based applications where users must be physically present in the same location hence the need for the development of a multi-user remote virtual environment [5, 12]

The development of remote multi-user virtual reality was started in the late 1970s by Richard Bartle and Roy Trubshaw. They created a remote multi-user VR system that allowed users to collaborate via a computer network. Interaction in the VR environment and visual cues were very limited given the network limitation and hardware at that time [6]. Du et al. [5] define remote multi-user virtual reality as a system to bring participants with different geolocations into the same virtual environment via a cloud-based network. This technology has several advantages. According to Octania [7], it allows the entire team to meet at any time without being physically present, which limits long-distance travel and subsequently optimizes the carbon and time footprint. On the other hand, it allows improved productivity and understanding of the project thanks to real-time visualization. Moreover, it allows for the improved efficiency of training. Indeed, Dede et al. [8] proposed to integrate this function into their virtual reality system to facilitate learning. They found that a remote multi-user virtual reality tool improved the method of collaboration and learning through virtual interaction. In the medical sector, the multi-user feature was integrated into VR technology by Schäfer et al. [9] to overcome people's phobia of the real world. Tests have shown that this virtual collaboration improves the treatment of several phobias.

2.2. Multi-user virtual reality in construction

BIM-based virtual reality technology is showing every day the potential of its application in the construction industry. However, there is not much research in the literature review dedicated to the application of remote multi-user virtual multi-user virtual reality experience in the construction industry. Among the studies we found, we can cite a study on remote multi-user virtual reality for communication [5], and remote multi-user virtual reality for safety [10].

Du et al. [5] proposed a cloud-based multi-user virtual reality system that uses the metadata of a BIM model to improve communication among project stakeholders in a virtual reality environment. The CoVR system allows for improving communication between stakeholders in construction projects. Indeed, the participants of a project are usually located at a distance. CoVR allows them to connect to a cloud server in the same immersive environment to discuss and solve design problems in real-time. It thus optimizes interaction in a multi-user interactive virtual environment [5].

The construction industry experiences many fatal and non-fatal workplace accidents each year. Proper safety training for workers is therefore mandatory. The use of new technologies such as virtual reality has proven to be more effective and motivating than traditional methods. Furthermore, its experiences are limited by a single user [10]. Thus, Moelmen et al. [10] developed an asymmetric multiplayer prototype based on virtual reality. This concept allows for representing a more realistic work environment. Indeed, it allows presenting a scenario with several hazards with unpredictable human interactions when using crane lifting operations or heavy machinery. This multiplayer VR system allows trainees to test their role on a dense and dynamic construction site and anticipate hazards thanks to the warning signals implemented in the prototype [10].

Luo et al. [11] proposed a prototype virtual reality-based multiplayer platform that supports safety knowledge. This system enables the interaction of multiple trainees in an immersive environment for simulating worker-equipment interactions. User performance can be monitored in real-time and stored in a database to analyze training effectiveness.

3. Research Methodology

To carry out our research project that targets the use of remote multi-user virtual reality in the construction industry to bring together construction project team members in an immersive virtual environment to support collaboration, we followed 4 main steps: Identification of the problem and motivation, the definition of the objective, design, and development and finally demonstration and evaluation.

3.1. Identification of the problem and motivation

First, we identify the problem based on our literature review completed in the first section. Indeed, virtual reality in construction as well as multi-user virtual reality at a distance are the main themes covered in connection with our research. This first section allows us to better understand the problem and identify the motivation of this research.

In the literature, we found that the use of multi-user remote virtual reality based on a BIM model is very limited in the construction industry. Typically, users must be present in the same location to immerse themselves in the virtual environment. Most virtual reality tools are limited to a single user, which does not enhance collaboration and communication. The development of a multi-user remote virtual reality platform based on BIM models can be a solution to bring together the stakeholders of a remote construction project in the same virtual environment to support collaboration.

3.2. Design and development of two prototypes

This step consists in designing and developing a prototype that answers the problems listed in the previous step. We will design two prototypes based on two different tools. (Photon Unity Networking " PUN2 " from Unity3D and Vizard). The development process of each prototype is divided into 3 stages: The pre-VR stage, the basic VR configuration stage, and the VR multi-user remote configuration stage. To develop the two prototypes, we used several tools that are available in the LaRTIC lab.

For prototype 1, we used the video game engine Unity3D and Photon Unity Networking (PUN2) since free versions are available. For prototype 2, we used Autodesk Revit. It is available for free to students and allows us to export the BIM model to an FBX file. We also used 3DsMAX to import the FBX file and export the BIM model to an OSGB file for transfer to Vizard Inspector. To create the virtual reality application, we used the Vizard application. To configure the remote multi-user feature in Vizard, we used two enterprise licenses of Vizard available at the research lab. The configuration is based on the integrated clustering-based collaboration module of vizard.

Finally, to live the multi-user remote virtual reality experience, we used the Oculus Quest headset, the 3D glasses, and the PPT wand of the multi-projection system (CAVE) installed at the lab.

3.3. Demonstration and evaluation

In this step, we presented a use case for each proposed tool. We then defined a hypothetical test scenario for each tool to perform our demonstration. The purpose of a test scenario will allow us to evaluate the usefulness and ease of use of the two applications in the construction industry. The two remote multi-user virtual reality support systems will be evaluated according to the following criteria:

- The maximum number of users in the same multi-user VR environment remote VR environment

- Voice communication between users in the VR environment.

- The type of network required (local/cloud) for the user to connect in the multi-user VR environment the remote multi-user VR environment.

4. Main results

In this section, we present the results of the comparative study of the two remote multi-user virtual reality systems. We will start with a detailed presentation of the use of the Unity3D and Photon PUN2-based system. We will then detail the use of the Vizard-based system. We will focus on the main process steps, including the PRE-VR step (integration of the BIM model into the VR system), the VR-Basic configuration step, and the VR-Remote multi-user configuration step. We will then define several criteria to characterize the potential of the two systems studied.

4.1. Remote multi-user VR environnent based on Unity3D + Photon PUN2

In this section, we will present the first process steps regarding the development of a remote multi-user VR environment based on the Unity3D + PUN2 game engine. Our method consists of integrating a cloud-based network into the Unity game engine to facilitate multi-user interaction in the virtual environment. It is composed of 3 main steps which we detailed in Figure 1.

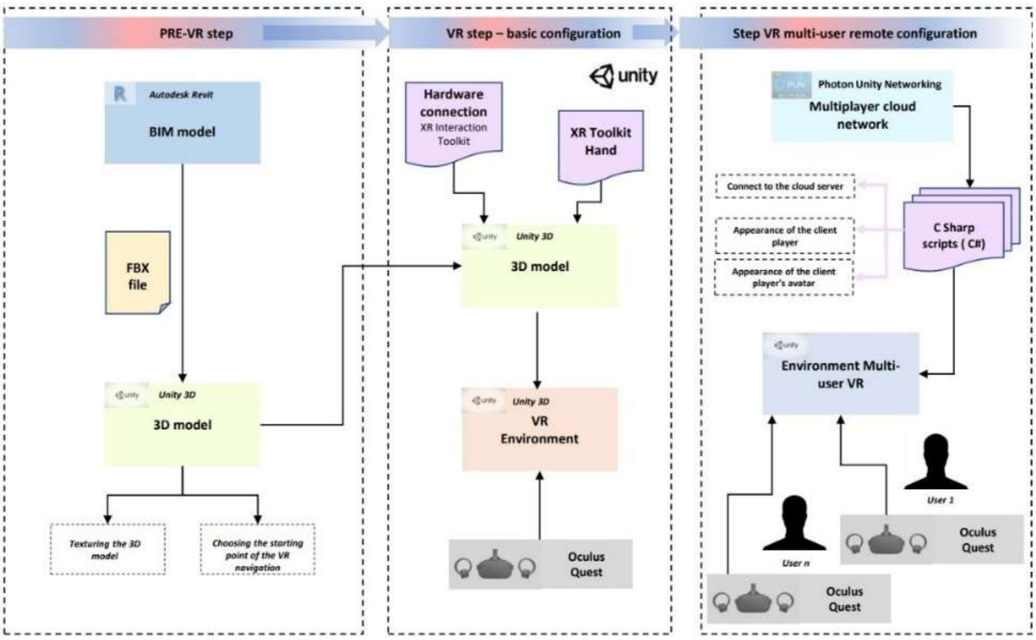


Figure 1: General development process of a multi-user VR environment based on Unity 3D + PUN2

We started to configure the VR environment in the Unity 3D game engine. Then, we implemented the Photon Unity Networking (PUN) library as a multi-user platform in Unity. To do this, we need to create a new Photon cloud account (free) on the official website. After that, we created the Photon cloud application The next step would be to connect to the PUN cloud server. For this, we created a code (script) with Microsoft Visual Studio that uses the C# programming language (C-Sharp).

Text-based communication is very limited in virtual environments due to the slow nature of VR keyboards. Voice communication can be a very interesting and more efficient collaborative solution. PUN 2 has simplified the process of implementing this functionality. Indeed, it has Voice over IP (VOIP) technology that allows the integration of a voice interactive system in the cloud server. Users who are present in the same VR environment can talk to each other with voices and make conversations. The virtual VOIP conversation is only possible if the two avatars are in proximity.

4.2. Remote multi-user VR environment based on vizard

In this section, we will present the process steps concerning the development of a multi-user VR environment based on vizard. The diagram below (Figure 2) summarizes the process of the proposed method concerning the development of a multi-user virtual reality environment based on Vizard.

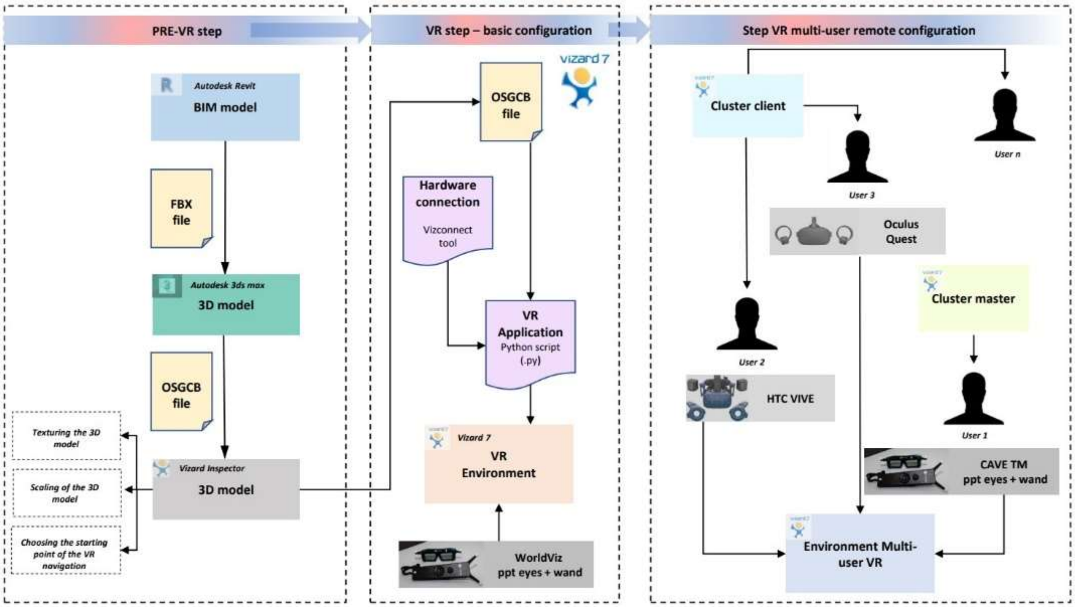


Figure 2: General process of developing a multi-user VR environment based on Vizard

The BIM model in Revit is first exported to an FBX file. The FBX file is then imported into 3DsMAX. At this stage, we noticed that the FBX file is very heavy to import into 3DsMax. To solve this problem, we had to clean up the model on Revit to make it light (remove parts, lights, etc.). Then, the 3D model in 3DsMAX is exported to an OSGB file using the "OSG Exporter" plugin. To have the 3D model at scale in the VR environment, it is necessary to adjust it in the export settings. The OSGB file is then introduced into the Vizard inspector. At this stage, it is possible to modify the scene by adding shadow and light and to modify the textures of the model's sub-parts if necessary. In addition, we can choose the starting point of the virtual visualization in vizard. To know the point of origin, we must add an avatar in the scene and then move the 3D model so that the avatar is in the desired initial position. In the second step, another script has been developed with Vizard allowing to execution of the virtual reality application.

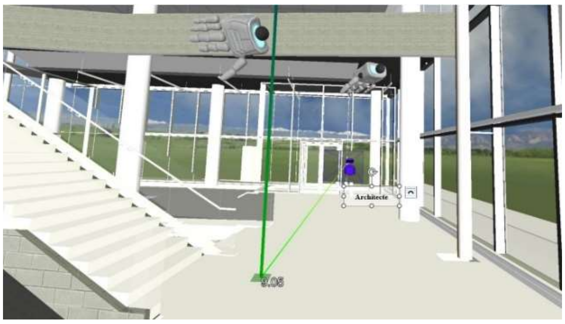
To interact and collaborate in the VR environment, we tried to add 2 interesting tools to our VR application:

- The Pencil Tool: This tool allows you to make annotations in the VR environment or on the surfaces of objects. To add this function to our VR application, we improved our first script based on the documentation of vizard.

- The tape measure tool: This tool allows to measurement of the distance between two points in the VR environment. Indeed, when the user places the first point, the second point will automatically be placed orthogonally in front of the first point. The Vizard tape measure works with any geometry that exists in the VR environment.

This step involves configuring multiple users to be able to view the same virtual environment remotely with Vizard. This can be configured with several VR headsets (Oculus Quest, HTC VIVE Pro ...) and with the CAVE (Cave Automatic Virtual Environment) system. So, we used the cluster tool (cluster client/cluster master) of vizard. The implementation of the remote collaborative VR environment with the cluster tool requires that all users are connected to the same local network and that all machines have an enterprise license of Vizard. With the demo version, the cluster is limited to 5 minutes of execution.

a



b

Figure 3: (a) The measuring tool in the multi-user VR environment; (b) the annotation tool in the multi-user VR environment

4.3. Comparison of two systems studied.

In this section, we will compare the two remote multi-user virtual reality support systems Unity3D + Photon Unity networking (PUN2) and Vizard. The results of the comparison can be seen collectively in Table 1 and are described in detail in the following paragraph.

Table 1. Comparison of the two tools proposed to support a remote multi-user VR environment based on a BIM model

Criteria	Sub-criteria	Remote multi-user VR based on Unity3D+PhotonPUN2	Remote multi-user VR based on Vizard
General	Price of a license	Free	Business license 2000$
	Number of users	20	No limits
	Open source	No	No
	Limitation (free version)	No limits	5min of execution
Type of network	Local Area Network (LAN)	Yes	Yes
	Cloud-based network	Yes	No
Tools for collaboration	Voice communication	Yes	No
	Annotation tool	Yes	Yes
	Measuring tool	Yes	Yes
Friendliness and Programmability	Visual inspection	Yes	Yes
	Programming language	C-Sharp (C#)	Python (Py.)
	Conviviality	Complicated	Simple
Supported hardware	Oculus Quest Compatibility	Yes	Yes

	VR CAVE compatibility	No	Yes
	Oculus Rift S Compatibility	Yes	Yes
	HTC Headset Compatibility	Yes	Yes
Interconnectivity	File type of the 3D model	FBX file	OSGB file
	Preservation of the texture	No	Yes
	Retention of model information	No	No
Realism graphic	Realism	Very good	Depends on the 3D model
	Light	Good	Complex
	Shadow	Automatic	Manual

General criteria:

The number of users in the remote multi-user environment is a potential sub-criterion for our comparison. The maximum number of users for the multi-user VR application based on Unity3D and Photon PUN2 (free version) is limited to 20 people while the number of participants is unlimited if we use the Vizard application. On the other hand, Unity3D and Photon (PUN2) are free, but they are not open-source. However, Vizard is available in several versions, and it is not open source. The multi-user version costs 2000$. The free version limits the execution time to five minutes.

Network type:

The type of network is another criterion for comparing the two proposed tools. To run the vizard application in multi-user mode and share the same virtual environment with team members, all users must be connected to the same local network. The geographical distance between users will be very limited because of this requirement. For example, it will not be possible to collaborate in the VR environment with team members who are located in another city using the Vizard application. However, the Unity and Photon (PUN2) based multi-user remote VR application uses a cloud network thus allowing users, with different geolocations, to connect and collaborate in the same virtual environment.

Collaboration Tools:

Collaboration tools are the second criterion for comparison. The multi-user Vizard application based on cluster nodes (master + clients) does not support voice communication between users. However, talking to each other with voices and making conversations between users in the virtual environment is possible with the VR application based on Unity and Photon (PUN2). Regarding the tools for interaction with the VR environment, Vizard has built-in tools such as the pencil for making annotations and the tape measure tool for taking measurements. Its tools are also available on the Unity game engine, but we did not integrate them into our application.

Supported hardware:

We used several other criteria to make our comparison such as compatibility with different VR hardware. Indeed, the Vizard application works with most virtual reality hardware through the "disconnect" display and tracking configuration tool.

For example, one user can use the CAVE system, the second user wears the Oculus Quest (HMD) video headset, and the third user uses the HTC VIVE headset and can meet in real-time in the same virtual environment. Moreover, the Unity3D-based application is compatible only with VR headsets (HMD, HTC VIVE). During our research, we explored a solution to integrate the Unity3D game engine into a CAVE system: MiddleVR. We did not test this solution because of costs and the unavailability of an educational license.

Usability and programmability:

The Vizard tool works with the Python programming language (Py.). To create a VR application with vizard, it is necessary to develop a script, many of the basic features of which are already provided in the application's documentation. However, Unity3D and photon (PUN2) use the C-Sharp (C#) programming language which is more difficult to understand.

Interconnectivity:

Interconnectivity with BIM software is another criterion that should not be overlooked. During the Pre-VR stage, the BIM model must be converted to an FBX file to integrate it into the Unity +Photon PUN2-based remote multi-user VR application, whereas the BIM model must be converted to an OSGB file to integrate it into the Vizard-based remote multi-user VR application.

5. Demonstration and evaluation

5.1. Demonstration of the Test Scenario

5.1.1. Scenario 1 based on remote multi-user VR using Unity3D + PUN2

In our hypothetical scenario, three users A, B, and C were using this application. Each participant was wearing the Oculus Quest video headset. The connection of each VR headset to the application is via Oculus Link, which connects the headset to the computer. User A played the role of the project owner who was not satisfied with the design of the coffee shop. User B played the role of an architect who is trying to redesign the design of the café according to the client's requirements. User C played the role of an interior Designer who was helping the architect redesign the coffee shop. As shown in Figure 56, the three participants are conducting the meeting in the same virtual environment.

Although the three users are not in the same location, the architect, interior designer, and owner, were able to meet in the same VR environment where they could discuss possible solutions to the problem during the meeting using the real-time voice tool (VOIP) integrated into our application. This voice system allows to stimulation of natural conversations. the voice is distributed according to the distance between the avatars of each user in the VR environment. This application allows a better communication approach between the project stakeholders compared to a traditional design review using 2D drawings or 3D models. This could minimize communication costs in the construction process.

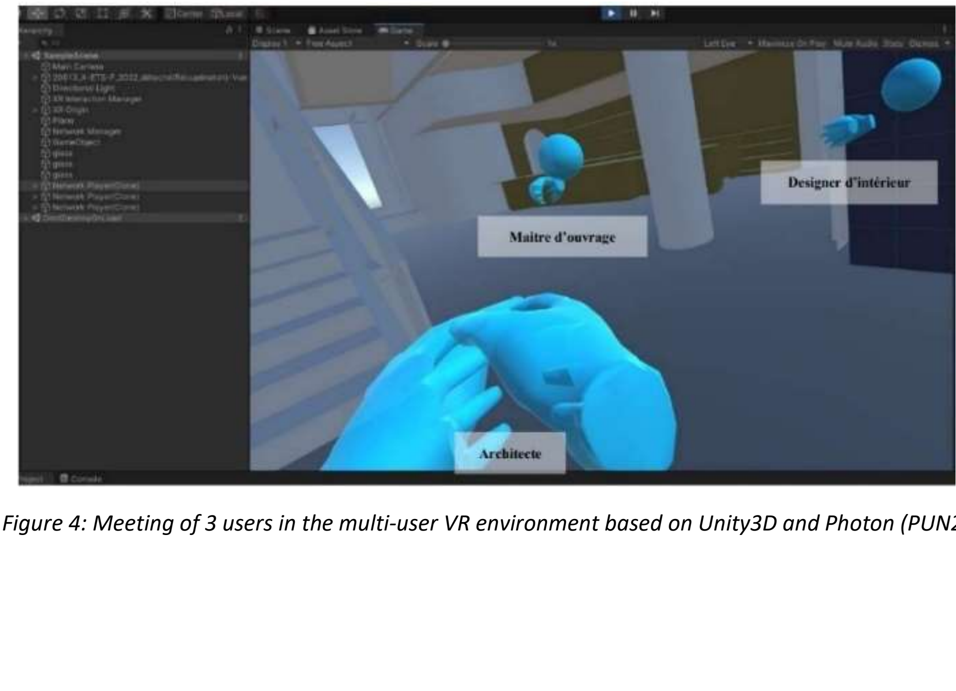


Figure 4: Meeting of 3 users in the multi-user VR environment based on Unity3D and Photon (PUN2)

5.1.2. Scenario 2 based on remote multi-user VR using Vizard

We have imagined a hypothetical scenario to demonstrate the usefulness of Vizard's remote multi-user VR environment. It is a design coordination meeting between two members C and D of the Pavilion D construction project team. We used 2 machines for our demonstration. The first machine is a Lenovo workstation (ThinkStation). It is linked to the 3-wall multi-projection virtual reality system (VR-CAVE) installed in our LaRTIC lab. It is equipped with a Quadro RTX 6000 graphics card. The second machine is an Alienware laptop. It is equipped with an RTX 3080 graphics card and linked to the Oculus Quest headset via Oculus Link. User C, who played the engineer, was using the Oculus Quest VR headset. User D, playing the role of the architect, used the 3D stereoscopic glasses and PPT wand of the CAVE-VR system.

The architect and engineer were able to meet in the same virtual environment from their respective remote locations. Both meeting participants can see each other, move around, and explore the 3D model to review the design from different angles without being limited to a single viewpoint as in 2D drawings. Each user can use his laser pointer as a measuring tool to verify that spaces meet construction standards.

Figure 5: Meeting between architect and engineer in remote multi-user VR environment based on vizard

5.2. Evaluation and discussion

In this section, we discuss the potential benefits that the two systems Vizard and Unity3D based on Photon PUN2 can bring to the construction industry as well as their limitations in supporting a remote multi-user virtual reality environment dedicated to the construction sector.

The two proposed systems Vizard and Unity3D+Photon PUN2 have the potential to play an important role in the construction industry. They enable the creation of a multi-user remote virtual reality environment that can bring many benefits to the industry, such as

Increased efficiency: Remote multi-user VR environments can be used for remote collaboration, project management, and virtual meeting allowing for more efficient teamwork while reducing the need for travel.

Improve design quality: Remote multi-user VR environments can be used for design review, allowing stakeholders to navigate and coordinate together in real time in the virtual environment to identify potential problems before construction begins.

Improve communication: Remote multi-user VR environments also improve communication between construction project teams, making it easier to understand the project and identify potential problems early on.

While Vizard and the Photon PUN2-based Unity3D game engine can be useful tools for VR collaboration in construction, they have limitations that must be considered:

Integration with BIM models: both proposed tools have limitations in integrating BIM models. The models must be converted into a format readable by each software. This conversion does not allow the transfer of model data into the VR environment. This makes the use of VR collaboration tools difficult and inefficient for reviewing and analyzing BIM models in real-time.

Technical Knowledge: Both Vizard and Photon PUN2 require a certain level of technical knowledge in programming languages (Python / C-Sharp) to use them effectively. This can make it difficult for some users such as non-technical members to participate in the collaboration session in the remote multi-user VR environment. In addition, Vizard and Photon PUN2 are not widely used in the construction industry, making it more difficult to find experienced consultants.

Cost: The cost of the enterprise license for the vizard tool is relatively high, which may limit the accessibility of this application, especially for small and medium-sized construction companies. In addition, both proposed systems require powerful computers and dedicated VR hardware to function properly, which may be beyond the budget of some companies.

6. Conclusion and future work

We can confirm that the two remote multi-user virtual reality support systems Vizard and Unity3D based on Photon PUN2 have the potential for use in construction with BIM models. However, both of its solutions have allowed us to identify some areas for improvement. Future work could include:

- Improving integration with BIM models: ways need to be developed to be able to transfer BIM models without losing model data into the Photon PUN2-based VR environment of Vizard and Unity3D so that remote VR collaboration can be better explored for real-time review and analysis of BIM models.

- Develop new functionalities: identify new use cases and develop new collaboration tools in the VR environment (screen capture, VR annotation export).

- Compatibility improvement: Develop a tool for the Unity3D game engine to be used with the CAVE multi-projection VR system.

References

[1] Boton, C., & Forgues, D. (2018). Practices and processes in BIM projects: an exploratory case study. Advances in Civil Engineering, 2018, doi: 10.1155/2018/7259659

[2] Boton, C., Rivest, L., Ghnaya, O. et al. (2021). What is at the Root of Construction 4.0: A Systematic Review of the Recent Research Effort. Arch Computat Methods Eng 28, 2331–2350, doi: 10.1007/s11831-020-09457-7

[3] Churchill, E. F., & Snowdon, D. (1998). Collaborative virtual environments: an introductory review of issues and systems. virtual reality, 3(1), 3-15, doi: 10.1007/BF01409793

[4] Redfern, S., & Galway, N. (2002). Collaborative virtual environments to support communication and community in internet-based distance education. Journal of Information Technology Education. Research, 1, 201, doi: 10.28945/356

[5] Du, J., Shi, Y., Zou, Z., & Zhao, D. (2018). CoVR: Cloud-based multiuser virtual reality headset system for project communication of remote users. Journal of Construction Engineering and Management, 144(2), 04017109, doi: 10.1061/(ASCE)CO.1943-7862.0001426

[6] Dieterle, E. (2009). “Multi-user virtual environments for teaching and learning.”Encyclopedia of multimedia technology and networking,2nd Ed., IGI Global, Hershey, PA, 1033–1041, doi: 10.4018/978-1-60566-014-1.ch139

[7] Octania, (2022), La réalité virtuelle dans le travail collaboratif à distance, spotted at: https://www.octarina.com/vr-collaborative-teletravail/ ,on 11 December 2022.

[8] Dede, C., Nelson, B., Ketelhut, D. J., Clarke, J., et Bowman, C. (2004). " Design-based research strategies for studying situated learning in a multi-user virtual environment ". "Proc., 6th Int. Conf. on Learning Sci- ences, International Society of the Learning Sciences, Santa Monica, CA, 158-165, https://citeseerx.ist.psu.edu/document?repid=rep1&type=pdf&doi=334b8d11eeebc6072c0224eb6bdb01414d942400

[9] Schäfer, P., Koller, M., Diemer, J., et Meixner, G. (2015). " Développement et évaluation d'un système de réalité virtuelle avec suivi intégré des extrémités sous l'aspect de l'acrophobie. "Proc., SAI Intelligent Systems Conf. (IntelliSys), IEEE, New York, 408-417, doi: 10.1109/IntelliSys.2015.7361173

[10] Moelmen, I., Grim, H. L., Jacobsen, E. L., & Teizer, J. (2021). Asymmetrical Multiplayer Serious Game and Vibrotactile Haptic Feedback for Safety in Virtual Reality to Demonstrate 79 Construction Worker Exposure to Overhead Crane Loads. In ISARC. Proceedings of the International Symposium on Automation and Robotics in Construction (Vol. 38, pp. 613-620). IAARC Publications, doi: 10.22260/ISARC2021/0083

[11] Luo, X., Wong, C. K., & Chen, J. (2016). A multi-player virtual reality-based education platform for construction safety. In 16th International Conference on Computing in Civil and Building Engineering (pp. 1637-1643), http://www.see.eng.osaka-u.ac.jp/seeit/icccbe2016/Proceedings/Full_Papers/207-205.pdf

[12] Boton, C. (2018). Supporting constructability analysis meetings with Immersive Virtual Reality-based collaborative BIM 4D simulation. Automation in Construction, 96, 1-15, doi: 10.1016/j.autcon.2018.08.020

NEW HORIZONS FOR A WORKER-EFFECTIVE TRAINING METHOD IN THE AEC SECTOR

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Abstract
The training of site professionals is typically perceived as being monotonous, and ineffective in terms of information assimilation and retention. Furthermore, traditional training approaches such as lecture-based presentations, have been demonstrated to be unsuccessful at engaging site workers, resulting in decreased attention and motivation. This paper aims to develop the framework for gamified training, of site workers. It is intended to value the requirements that European H&S standards expect to be kept under surveillance. The outcome of this work is the definition of a new reward procedure focused on ongoing improvement via feedback to low-scoring individuals. Multiple screen boards are designed to facilitate key context interaction and possible reactions. This study outlines two theoretical applications of training, the first applicable transversally to many situations (i.e. Educational Construction Site Information Modeling) and the second as a site-specific solution based on its digital twin (i.e. Mockup Construction Site Information Modeling) intended to accurately foresee and train workers for dangerous operations.

Keywords: Building Information Modeling, Construction Site Information Modeling, Digital Simulation, Gamification, Training

1. Introduction

The Building Information Modeling (BIM) methodology provides increasingly widespread applications within the Architecture, Engineering, and Construction (AEC) industry. From the modelling of aforementioned disciplines, a new one related to construction processes has been added, linked to the operations phase, which specializes more than a managerial 4D analysis by the in-depth study and which aims to understand how to improve site management from logistical, sustainable, health, and safety stance. Therefore, we wish to investigate a fundamental aspect of how these enhancements can be attained. To ensure the safe performance of activities, it must be remembered that the Directive 89/391/EEC - OSH recommendations must not only be stated in technical documents but must also be translated into good practice on the construction site. Therefore, instruction and training of personnel are required for this to occur.

The issue of correct training involves not only the theoretical information provided, but also, from a psychological standpoint, how this information is transferred. Therefore, it is necessary to develop a worker-effective training method for the AEC industry.

The purpose of this work is to investigate possible scenarios that can be developed as training with the support of gamification logics that have proven to be useful in terms of engagement and return on learning [1]. Specifically, the goal of this investigation is to determine whether or not a particular scenario can be developed as training [2].

A portion of the effort involved focusing on difficulties including 1) planning training requirements; 2) creating narratives that are appropriate for the location and fit the demands; and 3) dealing with immersive virtual reality (i-VR) technology.

2. Literature review

We will make an effort to provide answers to questions such as, "What is the definition of gamification?" Which areas does this pertain to specifically? What are some particularly noteworthy examples? How can we interact? In order to respond to these questions, we will construct a discourse that first offers the reader a series of definitions of gamification, distinguishing it from serious games, and then outlines the most typical experiences that may be achieved via the use of gamification.

The term "gamification" has been widely adopted by the scientific community, with its origins traced back to British programmer Nick Pelling. Pelling initially coined the term in 2002 to refer to playful applications that were not solely intended for entertainment purposes. This has been noted in various academic sources, including [3], [4], and [5]. The clarification of the distinction between Gamification and Serious Games is essential to fully grasp their significance, as they are two distinct yet complementary concepts, despite their initial chronological emergence. The use of the term 'productivity games' [6] in lieu of 'playful design' [7] is a frequently encountered phenomenon. However, it can be argued that 'gamification' has established itself as a widely recognized term. As per Detering's analysis, the term "gamification" encompasses a discrete set of phenomena, including gameful interaction, and gameful design. These concepts are distinguishable from established notions such as playfulness, and design for playfulness. To properly understand these concepts, it is worth to refer to the adapted Figure 1 from [8].

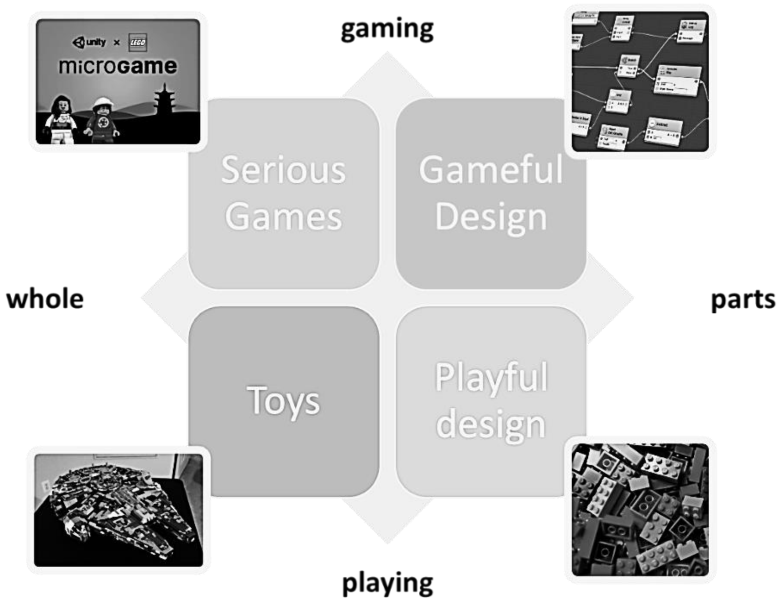

Figure 1 – Compass to navigate SGs and Gamification

The term "gamification" is currently used to refer to two interrelated concepts, the first trend pertains to the growing acceptance, endorsement, and ubiquity of (video) games in everyday use, as documented by [9] and [10]. The second concept suggests that video games, being primarily designed for entertainment, possess the capacity to motivate players to engage with them at an unrivalled level and for a prolonged duration. Consequently, it is suggested that game mechanics can be utilized to enhance the appeal and engagement of non-game products and services [11].

The rapid evolution of visualization technologies, such as virtual reality (VR), augmented reality (AR), and mixed reality (MR), has numerous consequences for the AECO industry. These visualization tools are facilitating new channels of communication and collaboration among stakeholders. the incorporation of gamification with visualization technologies has led to the emergence of new applications and effects, such as skills teaching, health and safety training, and behavioral investigations. These gamified applications resemble the fundamental structure of SGs [12]. Several references provided an increasing number of evidence, that by comparing SGs and traditional education methodologies in construction health and safety training and skill development the former results as more effective than conventional training methods [13].

3. Development

In order to develop a training application, it was necessary to develop a logical method that would underpin the learning process in which the worker would participate. Two main areas were identified for this purpose. Figure 2 provides a concrete illustration of the relationship between the design and the development of the game and its components. The parts of the diagram are logically ordered: (1) description, (2) event, (3) criticality, (4) requested action, and (5) learning objective.

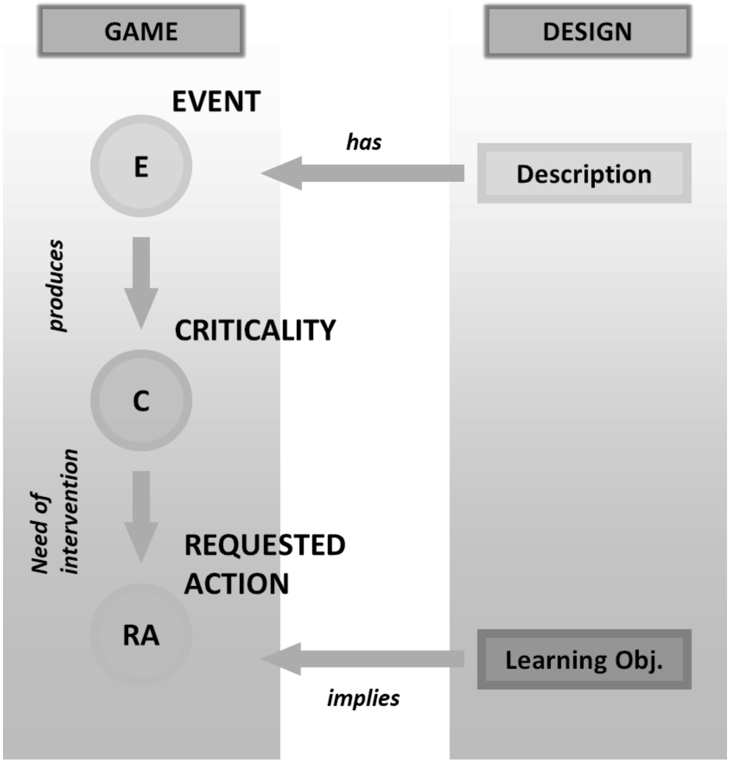

Figure 2 – Game/Design swim lanes

3.1. Description

The initial phase in the design industry is description. This is a normal language description and not a machine language description. The purpose of the description is to provide information to the developer and highlight, in connection to the process, the events that must be supported by the application. The objective is to offer indicators that enable the programmer to trigger the scene and level, hence initiating the event. The relationship between the description and the events is 1 to 1. For each event, a description must be provided to assist computer production work by elucidating the manner in which the occurrences are to unfold.

3.2. Event

The second part of the process translates the trigger in the game's description and references to the macro region of the game. This phase denotes the start of each scenario and level that will be encountered within the program. The trainee, the appointed work supervisor (AWS), sees many characters appear and then, in accordance with the functions that are expected of them, those characters immediately begin engaging in the activities that are the primary focus of the trainee's attention. An exciting opportunity lies in the possibility that events might be linked to the activities that are being systematized in the ergotechnical project. This 4D program, the GANNT schedule, can be developed with finer precision, therefore this possibility represents a win-win situation. The events have been described and developed according to real scenarios experienced by the authors in infrastructure sites both in terms of operations and phasing.

3.3. Criticality

The most pertinent aspect of the procedure outlined here is the effective translation of the event's criticality. This section must be created with great care, as it is the linchpin of the success of the subsequent phase's response. The beginning event must be able to elicit the anticipated sensation of criticality so that it may be calibrated against the expected response in order to meet the learning aim. Criticality is developed with unfavorable on-site behaviors, such as the occupation of an excavator's buffer zone, rather than the execution of specific activities by non-expert worker or even (and probably more serious) the absence of control over personnel. These are only a few instances of the key challenges that the European Directive 89/391/EEC – OSH tries to disfavor.

3.4. Requested action

The required action is the fourth phase of this scheme pertaining to the game production stack. This phase involves the randomness of the learner's response, so it is only possible to identify the most pertinent action. If successful, it is during this phase that the necessary procedures to be maintained on-site are learned. This phase is the design's synthesis, which is centered on the ability to make the response acceptable and consistent with the learning objective, as detailed below.

3.5. Learning objective

The final phase, the fifth, consists of defining the learning objective, which is designed to highlight what you want the learner to demonstrate. This section again pertains to the design phase and not the construction of the application game, since it is derived from the comprehension and, consequently, synthesis of the regulations pertaining to worker health and safety. This phase works together with the required action phase, as it is based on what is described here that one must consider the learner's recognition and scoring for the activity accomplished. One could conceive of a scenario in which there is not just a net score but also an automatic and discrete evaluation that allows for nuanced scoring. Capable of recognizing not only possible optimally coupled activities, but also acts that, while not exactly accurate, have a decent degree of success or at least don't completely fail.

3.6. Application schema

The scheme derived from the preceding description is depicted in Figure 3, which illustrates how the learner, and the instructor can interact via the back-end control system. The beginning of the activity corresponds with the learner's first choice between a Head Mounted Display (HMD) for a more immersive experience or a straightforward but equally immersive display, depending on the availability of the offered resources. Following this option, the instructor has the ability to monitor and verify the learner's actions through his display. Depending on whether or not criticality is identified, data on the participant's behavior is collected and stored in a separate database for data collection. If the requested action is carried out, a new value is recorded in the data collection database indicating whether the action was accurate. In both instances, the choice is preserved and organized in order to provide the learner with a comprehensive report upon completion of the virtual training. If the learner takes the correct action and is thus able to not only identify the source of the hazard but also take the most appropriate action to resolve it, the System assigns a score corresponding to the difficulty of the resolved criticality. The triggering event procedure is then repeated iteratively until the training is complete. Through the confrontation with the learning objective, the trainer is then able to provide feedback to the learner by processing the data stored in the data collection database in order to produce an improvement in the learner and thus confirm more closely that the training objective is actually successful and can be deemed successful.

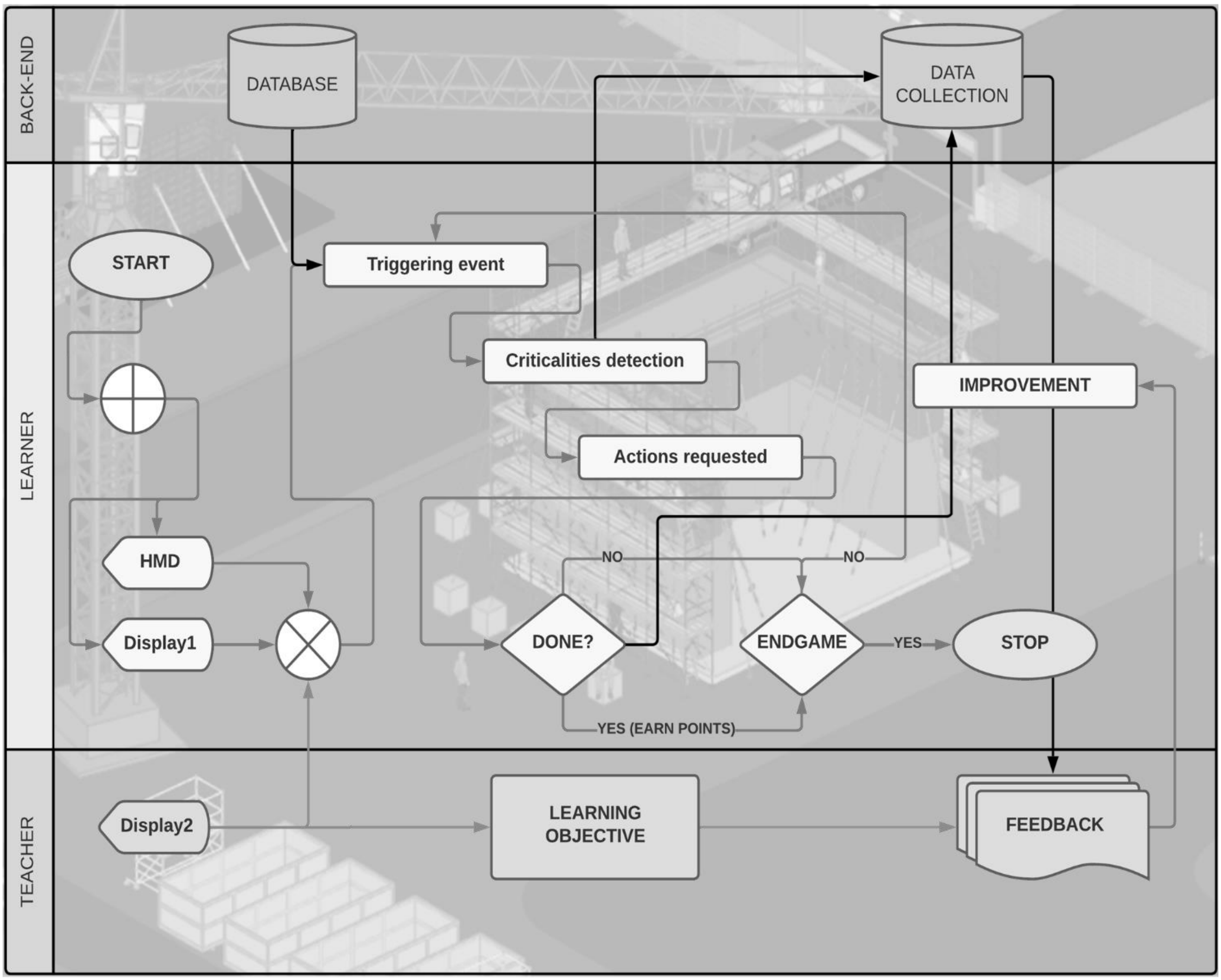

Figure 3 – Workflow

3.7. Scenarios development

In order to structure a worker-effective training experience, it was necessary to create a series of case studies that were representative of work in the context of infrastructure construction. The schematization proposed in the following image or table corresponds to that already presented in figure 2, where we find:

- Event;
- Description;
- Criticality
- Learning objectives;
- Requested action.

To enhance the specified fields, operational descriptions with a progressive time progression and a comprehensive breakdown of the work phases were developed. An illustration follows.

1. Provision of temporary transit prohibition barriers at overhead power lines using a box truck, unloading of the carrier in accordance with the procedure, and installation by an operating team

comprised of a team leader and an attendant, at the distance from the ground projection of the overhead power line specified by the applicable safety management plan (SMP). Elimination of the supply vehicle.

2. The delivery of a tracked elevating work platform (EWP) and a tracked mini-excavator on a low-bed truck, with ramps built up by the driver of the vehicle and machinery lowered to the ground by a qualified operator.
3. Using a mini excavator, prepare the space for the placement of aerial work platforms and the installation of prefabricated plinths for the building of overhead power line signal gateways. Planting topsoil in the region of the site. Installation of operationally configured EWPs at the northern gateway.
4. The delivery of prefabricated piles and plinths for the construction of portals using a hydraulic truck-mounted crane with caisson. Placing of plinths, raising of piles, and installation of signposts utilizing synchronized actions of a truck-mounted hydraulic crane and EWP driver, after stabilization of the vehicle by the driver, by an operating team comprised of a team leader and a competent worker.
5. Repetition of operations 3-5 by reversing the direction of the truck crane's arrival (to ensure the safety distances of the crane from the power line).

Event	Description	Criticality	Learning Objective	Requested Action
		Start Level 1		
The dump truck for supplying the barriers appears	The box truck positions itself in the shadow of the ground projection of the power line	When handling a telescopic boom, there is a risk of contact with the high-voltage line	Checking the correct positioning of the box van in relation to the projection of the power line	The site supervisor places the box van at a safe distance
Two workers from the contractor appear	the two workers are supporting the activities to be carried out	Unidentifiable workers may not be regularly employed	Verification of workers' identity	
	workers must be identifiable and identified	Unidentifiable workers may not be duly employed	Verification that the names of the workers correspond to those indicated in the SMP	The AWS verifies that the names match the contents of the SMP
A worker starts climbing onto the body of a dump truck	one of the workers starts a potentially dangerous activity	In case of slipping, the worker risks falling and injuring himself	Check that no dangerous situations are created in relation to the activity	The AWS must provide a ladder to access the skip

Figure 4 – Events schematization

4. Conclusion

The purpose of this work is to try to conceive of and sketch out a potential worker-effective training program that would improve information retainment for safer construction sites.

This resource's potential applications are not limited to the training of workers with generic scenarios involving the use of specified equipment or machinery. The application seeks to achieve more tangible benefits through the use of this instrument for specific and targeted training on each construction site. Educational Construction Site Information Modeling (E-CoSIM) refers to training applications in which prevalent scenarios can serve as representative settings for typical situations. In addition, one can refer to Mockup Construction Site Information Modeling (M-CoSIM) for applications related to the construction site, which involves the development of a true geometric and information model that is representative of the reality in which workers will be required to perform their duties.

In both instances, it is believed that the proposed system will benefit the participation of employees in general and specialized training, and that the use of this resource will provide a tangible and direct advantage in mitigating risks on the construction site. The use of the M-CoSIM approach in this context is illustrative of the actual activities that will occur on the construction site, allowing the worker to practice and learn the correct procedures, even though mistakes that, unlike in the real world, will not harm him.

References

[1] Z. Zainuddin, S. K. W. Chu, M. Shujahat, and C. J. Perera, “The impact of gamification on learning and instruction: A systematic review of empirical evidence,” Educational Research Review, vol. 30, p. 100326, Jun. 2020, doi: 10.1016/j.edurev.2020.100326.

[2] Y.-C. Lin, Y.-H. Hsieh, H.-T. Hou, and S.-M. Wang, “Exploring students’ learning and gaming performance as well as attention through a drill-based gaming experience for environmental education,” Journal of Computers in Education, vol. 6, no. 3, pp. 315–334, Feb. 2019, doi: 10.1007/s40692-019-00130-y.

[3] C. Rigóczki, D. Andrei, and K. Györgyi-Ambró, “Gamification on the edge of educational sciences and pedagogical methodologies”, jATES, vol. 7, no. 4, pp. 79-88, Nov. 2017, doi: 10.24368/jates.v7i4.12.

[4] M. Jakubowski, “Gamification in Business and Education” in ABSEL, 2014, pp. 339–342.

[5] A. V. Kamasheva, E. R. Valeev, R. Kh. Yagudin, and K. R. Maksimova, “Usage of Gamification Theory for Increase Motivation of Employees,” Mediterranean Journal of Social Sciences, Feb. 2015, doi: 10.5901/mjss.2015.v6n1s3p77.

[6] M. McDonald, R. Musson, R. Smith, “The Practical Guide to Defect Prevention”, Microsoft Press, 2008.

[7] J. Ferrara, “Playful design : creating game experiences in everyday interfaces”, Rosenfeld Media, 2012.

[8] S. Deterding, D. Dixon, R. Khaled, and L. Nacke, “From game design elements to gamefulness,” Proceedings of the 15th International Academic MindTrek Conference: Envisioning Future Media Environments, Sep. 2011, doi: 10.1145/2181037.2181040.

[9] T. Chatfield, “Fun Inc.: Why Gaming Will Dominate the Twenty-First Century”, Pegasus, London, 2005.

[10] D. Helgason, Trends | Unity Blog [Online]. Available: https://blog.unity.com/technology/2010-trends

[11] G. Zichermann, C. Cunningham, “Gamification by Design: Implementing Game Mechanics in Web and Mobile Apps”, O’Reilly, 2011.

[12] Z. Feng, Y. Gao, and T. Zhang, “Gamification for Visualization Applications in the Construction Industry,” Industry 4.0 for the Built Environment, pp. 495–514, Dec. 2021, doi: 10.1007/978-3-030-82430-3_21.

[13] J. T. Albers, Y. Li, G. Lemasters, S. Sprague, R. Stinson, and A. Bhattacharya, “An ergonomic education and evaluation program for apprentice carpenters,” American Journal of Industrial Medicine, vol. 32, no. 6, pp. 641–647, Dec. 1997, doi: 10.1002/(sici)1097-0274(199712)32:6<641::aid-ajim10>3.0.co;2-1.

THE ROLE OF PROJECT SUPERVISOR WITHIN THE BIM EXECUTION PLAN

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Abstract

In the AECO sector, the BIM approach is used to manage and exchange information between the different stakeholders involved in the development of a project. Central models, available on CDE, store the information that could be retrieved according to the role and to the specialism involved. Drawing the right set of properties is crucial for successful workflows, hence cross-information is fundamental to achieve information exchange between disciplines, managed by each BIM coordinator. According to ISO 19650 series the client specifies those requirements in the EIR, nevertheless, few cases show the implementation of Health and Safety measures in it. European Directive 89/391/EEC on health and safety (H&S) on workplaces and more specifically the directive 92/57/EEC addressing Project Supervisors can be both seen as a beacon in this field for their clear and neat list of compulsory and optional requirements. This work aims to create an integrated standard example to be used from the clients at the tender stage (pre-BEP) to verify and validate the completeness of H&S design outcome. Such integrations aim to facilitate the information flow among the different specialists reducing the occurrence of onsite accidents.

Keywords: BEP, CoSIM, Construction Site, Health and Safety, Project Supervisor.

1. Introduction

European Directive 89/391/EEC concerns the application of measures carried out to promote the improvement of the safety and health of workers in the workplace. Given the specific nature of a construction site and the necessity to have a defined figure, appointed in order to obtain workers' health and safety, the European Community then enforced Directive 92/57/EEC, introducing the role of the "Project Supervisor (PS) as "*any natural or legal person responsible for the design and/or execution and/or supervision of the execution of a project, acting on behalf of client*". Its role has since been variously interpreted by European country member parties blurring its definition in different ways.

Anyway, the Project Supervisor has the due to assure health and safety (H&S) both in the design and the construction phase of a project. To carry out the task, the PS needs specific tools and a number of information such as to analyze and assess if the design documentation includes health and safety construction issues, coordinated with all the other design disciplines.

The PS, as well as the employer, can refer his control activity to the thematic areas detailed by the 89/391/EEC as "General obligations on employers" where eight H&S prevention measures are detailed.

Acting in a BIM environment, the tool here proposed aims to help the PS in defining the appropriate level of H&S information need to be requested from designers. Then, designers participating in the tender will have to meet and enhance in their offer those requirements to receive the tender score from the PS. For the goal is necessary to specify the contents of the documents postulated by the standard ISO 19650-6: the EIR (Exchange Information Requirements) representing the call and the BEP (BIM Execution Plan), saying the answer.

Especially, since the EIR, drafted by the SP, establishes the hierarchies and requirements related to the exchange of information within a BIM process, it represents a key point in the tender process that incorporates within it the inputs of OIR (Organizational), AIR (Asset) e PIR (Project).

It is advisable that within the Organizational Information Requirements (OIR), construction site health and safety issues are cited as strategic corporate objectives in order to develop policies that safeguard workers' lives. As stated in EN ISO 19650-1 the Asset Information Requirement (AIR) specifies in the technical aspects the detailed information to incorporate and extend the addresses to the security requirements stated in the OIR; to ensure that information generated during the construction process is used to update the model for possible subsequent construction projects. As the appointing party should develop PIR's for Health & Safety in collaboration with their Nominated Individual for Health & Safety Information so should do the Lead Appointed Party for H&S coordination in design.

The role of the Nominated Individual for H&S can correspond to the PS or as an alternative can be an assistant.

By drafting an EIR and assessing the BEP, the SP then assumes a responsibility, normally borne by the principal in construction site H&S, by having the ability, capacity, and appropriate tools to define what information is relevant for the purpose of assessing potential damage events related to the construction activities specific to each design discipline. For their part, the designers will become aware of the potential risks inherent in their own project considering the possibility of eliminating or reducing them.

The creation of a Level of Information Need form by the Project Supervisor can therefore be the meeting point between these last two documents discussed: optimizing the bidding phase.

2. Literature Review

Good management and structuring of EIR help make more informed decisions, facilitate workflow and automate processes. The most widely used file format for drafting is a text-based document (DOC). Alternatively, the spreadsheet is also used for required information set standardization or commercial applications: they allow the drafting of EIRs containing predefined sets and rules for model checking [1].

Therefore, it's important to formalize and uniform the information request to facilitate the application of BIM to all projects.

In the AECO sector, many incidents occur due to limiting factors affecting the health and safety of workers, such as their poor training and the limited technologies implemented to prevent, and monitor risks. BIM aims to improve project management, planning, and validation, strengthening collaboration between the actors involved in a project and reducing risks and accidents [2].

BEP assists contractors in project coordination and management. Its compilation takes place at the beginning and during the various phases of the implementation of the project, facilitating the collection of data in the BIM model [3].

The site layout design and safety is an essential part of an effective integration process but is usually performed by manual, inefficient, and error-prone observation [4]. We have building designers who do not yet have a collaborative approach since the role of the Project Supervisor has not been fully learned following the European directive 92/57.

The use of interoperable BIM tools allows the development of a semi-automatic review of the compliance of projects with current regulations, improving the accuracy and reliability of the validation process [4].

3. Information flow setting

Following a BIM approach, according to ISO 19650:6, safety and health design needs a project information protocol containing the specific Exchange Information Requirements (EIR), the proper level of information need, the minimum acceptance criteria, and all those supporting information needed by the tenderer in order to reach a suitable response to the tender, delivering his preliminary BIM Execution Plan (pre-BEP). All the Design Teams tendering will find the tender documents in a Client's project Common Data Environment (CDE).

The first step to reach the goal has been the setup of a RACI matrix, so as to identify among the Client Project Team and the tendering Design Team those who are Responsible, Accountable, Consulted, and Informed within the documents workflow that is shown in Figure 1.

As the Client is represented by the Project Supervisor, according to 92/57/EEC, he will be always only informed about safety and health design tender development and its outcome. His only duty can be the appointment of the Client Project Team (CPT).

Assuming a general approach, the CPT has been composed of the Project Supervisor and his staff: the BIM Advisor, the Safety Advisor, and, after the preBEP delivery the Design Auditor. On the other side, the Design Team called to tender has been composed of the Design Manager and his staff: the BIM Coordinator, and all the Designers involved, including the Safety Coordinator (set by the 92/57/EEC), all of them assumed as BIM Specialists. The project phase considered is the so-called "project strategy phase" which includes the tender phase.

The actions involved in that phase will be the EIR and other inherent documents definition (responsible: BIM Advisor, accountable: Project Supervisor, consulted: Safety Advisor), preBEP drafting (responsible: BIM Coordinator, accountable: Design Manager, consulted: Designers), preBEP validation, referred to health and safety issues (responsible: Design Auditor, accountable: Project Supervisor, consulted: BIM and Safety Advisors) and tender award.

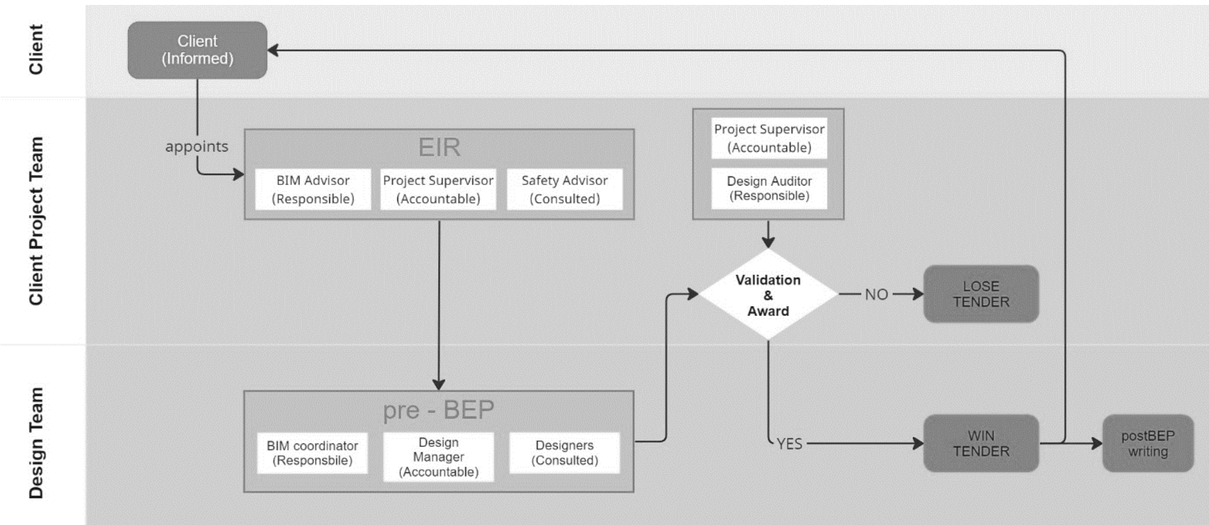

Fig. 1. RACI application and documents workflow

4. Working hypothesis

To establish the level of information need by the Project Supervisor, regarding health and safety on the construction site, the research focused on a very special "BIM object": manpower. A Construction Site Information Model (CoSIM), in fact, needs to be populated by a number of workers assumed as "objects" whose life, health, and safety have to be protected. All these "objects", inserted in strategic points of the CoSIM at different construction stages can enlighten dangerous operating situations to be examined.

As the research explores the tendering sub-phase of the strategic one, at a pre-BEP level is impossible to preview in detail those kinds of situations.

A suitable problem solution has been considered to add a list of possible damage events affecting workers with each design discipline involved in the project.

In the case of a client-proposed contract based on a master plan, each discipline and its pertinent designers have an overview of the principal operational criticalities in order to assess the risk level associated with damaging events. By implementing safety factors such as training and on-site/off-site monitoring, it is possible to minimize or, ideally, eliminate potential sources of risk.

5. Method

The chosen method by which H&S information is to be delivered, based on the requirements expressed by the Project Supervisor within the EIR, is the Information Delivery Specification (IDS) that works in parallel with the IFC standard thus fostering Quality and Assurance control over the information exchanged.

The analysis of the IFC schemas produced by BuildingSMART: 'IFC 4.0.2.1' (IFC4 ADD2 TC1) currently in force and 'IFC 4.3.x dev' now under approval revealed the absence of entities referring to construction workers.

Therefore, as an EIR operational tool, a computerized document dedicated to the S&H Level Of Information Need was proposed, interoperable between the Project Supervisor's team and the tendering Designers' team aimed at facilitating the validation activity by the Design Auditor and adjudication by the Project Supervisor, implementable as part of subsequent development of BuildingSMART's information schemes.

Consequently, the first step has been the definition of a new IFC entity referred to the figure of the worker to be associated with the risks to might be exposed in the execution of the works identified in the tender master plan for each project discipline. This entity was then associated with the skills needed to avoid them by providing information related to its education, information, and training.

The proposed entity is named **IfcConstructionWorker** and contains all the information necessary for the Project Supervisor to assess whether the Design Team has gained awareness regarding the need to adopt design measures for the prevention and protection of the health and safety of workers required by European Directive 89/391/EEC.

setting this information also allows the CPT to verify the actual consistency between the technologies proposed by the DT tendering for project implementation, the organization of the construction site, and the predictable protective conditions for workers.

Having identified the information that the IfcConstructionWorker entity has to contain, this was then schematized following the logic of openBIM, defining the PSet, Properties, and Value fields in which the information required by the European Directive could be entered.

At present, the IFC4_ADD2_TC1 scheme defines PSet_Risk to provide information related to risk assessment. This PSet, however, finds application to only the IfcProcess entity defined as a single activity or event that has sequence relationships with other processes of the same type and is therefore poorly integrated within the schema and poor in all the information that is of interest there.

The IFC4x3_ADD1 schema currently under development, conversely, has been expanded, modified, and integrated more within other entities. In fact, the new update provides for the applicability of PSet to entities, such as IfcGroups, IfcProduct, IfcTypeProcess, IfcTypeProduct, and the existing IfcProcess itself.

The analysis of these IFC entities revealed that they refer only to entities involving objects, groups of objects, or events. None of these admit the possibility of considering the risk applied to a person who, for example, uses an object predicted in the model.

Thus, the introduction of an IfcConstructionWorker is intended to have connected the PSet_Risk to allow the association of risk assessment with a representative entity of people. The IfcConstructionWorker entity will then have the ability to contain information about the type and nature of the risk, and properties already defined by buildingSMART within the schema. This would make it possible to provide from the outset a description of the generic nature of the context or hazard to which the worker might be exposed, using the property "RiskType."

The new BuildingSMART scheme expanded the "RiskType" property from IFC4_ADD2_TC1, going so far as to define 52 risk types, selectable in the PEnum_RiskType.However, the ability to choose from 52 risk types was found to be too broad, leading the Tendering Design Team to become confused when compiling and evaluating the risks that the worker may incur. For this reason, we propose to make groupings within the PEnum_RiskType to make the list smoother and less scattered. By way of illustration, a case is given in which we show how some of the 52 specific risks contained in the Pset of the IFC4x3ADD1 scheme can be grouped into at least 28 harmful events which the worker may incur. The following tables show some examples.

The first table shows how the reported PEnum_RiskTypes can be an enumeration of the Fall from height damaging event. The specific indication of the point from which it is possible to fall may be reported later, within other properties defined by the schema for the PSet_Risk such as the AssociatedLocation that allows precisely to indicate the location that can trigger the hazard.

Damage Event	PEnum_RiskType
Fall from height	Fallfromopenedge Fallthroughfragilematerial Fallfromscaffold Fall_ladder

Tab.1 “Fall from height” enumeration options

Table 2 shows how the malicious event "Struck by ... " can be representative of the enumerations provided by the IFC4x3ADD1 schema.

Damage Event	PEnum_RiskType
Struck by …	Struck Struckfallingobject Struckvehicle

Tab.2 “Struck by …” enumeration options

The scheme has also incorporated properties into the PSet_Risk to provide information regarding the procedure used to assess the risk, the actual value of the risk prior to the implementation of appropriate security measures, and the value after the security measures have been implemented.

The adopted risk mitigation method is specified in a dedicated property of the PSet_Risk. The ability to link this PSet to the proposed IfcConstructionWorker entity enables standardised input within a BIM model for the risk assessment information that must be validated by the Project Supervisor.

This streamlines and unifies the delivery of required information to the PS. The information submitted to the PS must also address the training of the IfcConstructionWorker-identified worker.

For this reason, three new PSets have been proposed for inclusion in the scheme currently under development that address the topic of worker training:

- ProfessionalTrainingEducation,

- ThoereticalProfessionalEducation,
- ProfessionalInformation.

The worker's training, suitability for performing the work with which he or she is associated, and knowledge of the technologies and equipment used are all information that must be provided because they are required by European Directive 89/391/EEC. The following is an excerpt from the organization of the mentioned PSets.

The PSet_ProfessionalTrainingEducation provides information regarding the hours of training that must be shown to have been carried out by the worker in the event that the worker is qualified to use construction site equipment or other equipment that requires specific qualifications.

The properties defined, with simulator and with real vehicle, express the number of hours achieved that can also provide the Project Supervisor with an understanding of the experience level of the worker identified by the company to perform the associated work.

The following image proposes the schema of the PSet_ProfessionalTrainingEducation just described.

Entity - New IFC	PSet	Properties		
		Properties	DataType	Description/Causes
IfcConstructionWorker	ProfessionalTrainingEducation			
IfcConstructionWorker	ProfessionalTrainingEducation	With Simulator	IfcNumber	Specifies how many hours construction worker was trained with the simulator for that working
IfcConstructionWorker	ProfessionalTrainingEducation	With Real vehicle	IfcNumber	Specifies how many hours construction worker was trained with a real vehicle for that working

Fig. 2. PSet_ProfessionalTrainingEducation

The second PSet, namely PSet_TheoreticalProfessionalEducation, enables the provision of information pertaining to the quantity of training hours that an enterprise is willing to offer to its employees.

The allocation of theoretical training hours could have taken place either at an external location or within the premises of the organization.

Entity - New IFC	PSet	Properties		
		Properties	DataType	Description/Causes
IfcConstructionWorker	TheoreticalProfessionalEducation			
IfcConstructionWorker	TheoreticalProfessionalEducation	On Site	IfcNumber	specifies how many hours construction worker followed theoretical lectures on site. Theoretical lectures on site could be about correct behavior during an emergency in a construction site, how to perform a specific work, …
IfcConstructionWorker	TheoreticalProfessionalEducation	Off Site	IfcNumber	specifies how many hours construction worker followed theoretical lectures off site. Theoretical lectures off site could be about correct behavior to follow, …

Fig. 3. PSet_TheoreticalProfessionalEducation

The study also took into account the provision of on-site information to workers regarding operational procedures and potential hazards of interference.

The final PSet_ProfessionalInformation seeks to furnish data on the duration of time that an employer will need to allocate for the purpose of informing their employees about the intricacies of their job responsibilities. This will encompass the employment of either conventional paper-based or digital tools, while also specifying the language employed for communication. The aforementioned property is widely regarded as being of utmost significance with regards to global labor mobility.

Entity - New IFC	PSet	Properties		
		Properties	DataType	Description/Causes
IfcConstructionWorker	ProfessionalInformation			
IfcConstructionWorker	ProfessionalInformation	by digital model	IfcNumber	It's important to inform construction workers the project they're realizing. Indicate how many hours they spend on a digital model to study it
IfcConstructionWorker	ProfessionalInformation	by drawing sheets	IfcNumber	It's important to inform construction workers the project they're realizing. Indicate how many hours they spend on drawing sheets to study it
IfcConstructionWorker	ProfessionalInformation	language	IfcString	identifies in which language information was given: official language and/or other

Fig. 4. PSet_ProfessionalInformation

6. Conclusion

The proposed OpenBIM approach, despite lacking a structured framework as previously outlined, was utilised in the design of the demolition and reconstruction site of the Teatro alla Scala's appurtenances in Milan. The systemization of the approach was carried out subsequent to the experience.

The research findings suggest that the proposed outcome can serve as an initial step towards transcribing information into computer language. This can be followed by the integration of the information into Building Information Modelling (BIM) authoring software and Employer's Information Requirements (EIR) documentation. The purpose of this integration is to facilitate the work of the Project Supervisor and the tendering Design Team.

References

[1] A. Tomczak, L. v Berlo, T. Krijnen, A. Borrmann, and M. Bolpagni, “A review of methods to specify information requirements in digital construction projects,” IOP Conference Series: Earth and Environmental Science, vol. 1101, no. 9, p. 092024, Nov. 2022, doi: 10.1088/1755-1315/1101/9/092024.

[2] A. Sidani, J. Poças Martins, and A. Soeiro, “BIM approaches for enhanced health and safety status in construction - protocol for a systematic review,” International Journal of Occupational and Environmental Safety, vol. 6, no. 1, pp. 1–8, Apr. 2022, doi: 10.24840/2184-0954_006.001_0001.

[3] G. Yang, K. Lao, W. Liu, X. Wang, T. Liu, and Z. Li, “BIM Execution Plan Compilation and Application in Singapore TUAS Water Reclamation Plant,” 2022 7th International Conference on Intelligent Computing and Signal Processing (ICSP), Apr. 2022, doi: 10.1109/icsp54964.2022.9778387.

[4] V. Getuli, S. M. Ventura, P. Capone, and A. L. C. Ciribini, “BIM-based Code Checking for Construction Health and Safety,” Procedia Engineering, vol. 196, pp. 454–461, 2017, doi: 10.1016/j.proeng.2017.07.224

[5] B. Farnetti, M. L. Trani, and N. M. Minotti, “OPTIMIZING COMMUNICATION FLOWS USING A STANDARD BIM ORIENTED RACI MATRIX,” Proceedings of International Structural Engineering and Construction, vol. 9, no. 2, Nov. 2022, doi: 10.14455/isec.2022.9(2).cpm-04