Lecture Notes in Civil Engineering

Scott Walbridge · Mazdak Nik-Bakht · Kelvin Tsun Wai Ng · Manas Shome · M. Shahria Alam · Ashraf el Damatty · Gordon Lovegrove *Editors*

Proceedings of the Canadian Society of Civil Engineering Annual Conference 2021

CSCE21 Construction Track Volume 2

Springer

Lecture Notes in Civil Engineering

Volume 247

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ISSN 2366-2557 ISSN 2366-2565 (electronic)
Lecture Notes in Civil Engineering
ISBN 978-981-19-0967-2 ISBN 978-981-19-0968-9 (eBook)
https://doi.org/10.1007/978-981-19-0968-9

This Springer imprint is published by the registered company Springer Nature Singapore Pte Ltd.
The registered company address is: 152 Beach Road, #21-01/04 Gateway East, Singapore 189721, Singapore

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Dr. Gordon Lovegrove is MBA/Civil Engineer with over 30 years of experience in smarter growth, housing, sustainable transportation, safety, economics, and project management. He was the point man that got the award-winning Universal Transportation Pass (U-Pass) for UBC that tripled transit use at both campuses. His current research focus is on zero-emission, hydrogen-powered rail (hydrail), including several industry partnerships to develop Canada's first hydrail switcher locomotive. He is Founding Partner of the SMARTer Growth Partnership (smartergrowthpartnership.ca), Associate Professor/Founding Member of UBCO's School of Engineering (ok.ubc.ca), VP Technical Programs for the Canadian Society of Civil Engineering (csce.ca), and Co-author of several best practice guides on sustainable development, health, and safety. He brings 20 years of practical industry development experience plus 14 years of engineering research and design expertise. His research team includes electrical, mechanical, and civil engineering graduate students, plus computer science coders and research assistants.

Discovery of Energy Performance Patterns for Residential Buildings Through Machine Learning

Araham Jesus Martinez Lagunas, Mohammad Askarihosni, Negin Alimohammadi, Azadeh Dezyanian, and Mazdak Nik-Bakht

1 Introduction

According to the 2019s Global Power City Index (GPCI), New York City (NYC) is ranked as the second major powerful city in terms of global attractiveness, with a total GPCI of 1543.2. This index evaluates six major aspects, from which environment' is one of NYC's lowest functions ranked as the 27th in terms of commitment to climate action, CO_2 Emissions, and renewable energy rate [7]. In 2011, the NYC Council updated the PlaNYC document titled "A Greener, Greater New York", which specifies the goal of reducing GHGE by 80% by 2050 [14]. To accomplish this, sustainability and efficiency of buildings have become major factors, since nearly 75% of NYC's GHGE comes from the energy used in buildings, with a major contribution of residential buildings [10]. Residential and commercial buildings collectively account for 40% of the U.S. total energy consumption, with an expected increase rate of around 5% by 2040 [21], and for 27% of the U.S. total delivered consumption from 2018 to 2050 [22].

The prediction and analysis of the building sector's energy consumption play a significant role in future decision making with regards to ameliorating not only the supply–demand management but also the design of different buildings aimed

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S. Walbridge et al. (eds.), *Proceedings of the Canadian Society of Civil Engineering Annual Conference 2021*, Lecture Notes in Civil Engineering 247,
https://doi.org/10.1007/978-981-19-0968-9_1

to reduce energy utilization [2]. Factors such as facility type, physical characteristics, geographical location, climate conditions, energy-consumption behavior of end-users, and type of installed equipment are useful to identify and study the energy use and GHGE of buildings [18]. Prediction models forecasting building energy demand and consumptions have been proposed by different researchers in previous studies at both building and national scales [17]. However, there is still a need for evidence-based and data-driven studies, which can identify and evaluate energy performance patterns of residential buildings from a multivariate view. This paper aims to identify, analyze, and predict energy consumption and GHGE intensity patterns for NYC's residential buildings based on the wide variation of building characteristics and historical energy data. Accordingly, the three main objectives of the study include (i) finding correlations and similarities among site EUI and GHGE intensity on the one hand, and weather condition, building characteristics, and location attributes on the other hand; (ii) identifying the main energy performance patterns by comparing most significant affinities between energy performance of residential buildings and contextual attributes, over time; and (iii) predicting quantitatively the GHGE Intensity, site EUI, and energy efficiency grades for residential buildings in NYC.

2 Previous Studies

The development of modern urbanization increases energy consumption, especially in the building sector, where CO_2 and other GHG emissions are raising the average temperature of Earth's climate system at a fast pace. The global energy demand is expected to increase by 30% by 2040. In parallel with this demand increase, a 50% reduction of GHGE through the adoption of more energy efficiency solutions is expected, to pursue the goal of limiting the global temperature to 2 °C degrees by 2040 [1]. Considering that on the one hand, roughly 40% of the global primary energy is consumed by buildings [15], and on the other hand, the GHG Emissions are positively correlated to the volume of energy consumption [19], the criticality of monitoring and reducing the energy consumption for building sector would be better highlighted.

Meng et al. [11] studied the correlation levels between multiple weather variables and the energy use for non-residential buildings based on change-point multivariable quantile regression models. Their effort resulted in finding significant associations between the type of the building, temperature, and energy consumption trends [11]. Haung and Hwang [5] studied the impact caused by the interface between outdoor climate and the indoor environment of buildings over their heating and cooling capacities. It was found that changes in the outdoor climate directly influence building energy consumption [5]. Both studies provide factual correlation evidence, but they are neither robust in finding building energy performance patterns, nor inclusive enough to be fully applicable for residential buildings because they do not consider other relevant aspects such as building characteristics or building location.

Hsu [4] analyzed 4000 multifamily buildings in NYC with the aim of predicting building energy consumption patterns by applying two modeling methods: first, cluster-wise regression (AKA latent class regression) and second, cluster validation methods (two-stage algorithms that use K-means and model-based clustering with regression). These models were validated through 20-fold cross performance evaluation, and Jaccard's Coefficient was used for measuring the stability of resulted clusters. As a result of comparing both clustering methods, it was found that cluster-wise regression has a higher prediction accuracy of 94%, but with unstable defined clusters, while K-means clustering method gives more stable clusters but very inaccurate predictions [4]. On the other hand, Kaskhedikar et al. [9] used EUI benchmarks from the Commercial Building Energy Consumption Survey database to predict future energy consumption through standard Linear Regression based on building-related features such as the area, building type, year built, and installed equipment. Random Forest algorithm was also implemented in the study to identify the most significant parameters influencing building energy consumptions for office and school building types [9].

Howard et al. [3] built a model to estimate energy end-use intensities (kwh/m^2) for residential buildings in New York City. Collected data included: electricity and fuel consumption, end-use ratios, ZIP Codes and total building floor area for each tax lot by building function extracted from the PLUTO database. They used multilinear regression technique to predict electricity and fuel consumption. For electricity and fuel consumption, 86% and 77% of the fitted building ZIP codes were predicted within ±20% of the measured consumption, respectively. These results provide the ability to estimate the dynamic energy consumption by end-use of each local tax lot in New York City [3]. The use of GIS for spatial identification of building energy consumptions can be a valuable tool for planning and tracking energy efficiency programs. However, collected end-uses ratios correspond to the total energy amount from all buildings within the Mid-Atlantic zone rather than to the one per building [3]. Jeffrey Kuo et al., In another relevant study, Jeffrey Kuo et al. [8] applied Logistic Tree Model technique to study the energy consumption performance of convenience stores in Taiwan, where key factors influencing building energy consumption per cluster were identified using the clustering regression technique [8]. Table 1 summarizes previous studies reviewed from the literature.

3 Methodology

The hybrid methodology proposed for this study is illustrated in Fig. 1. The study begins with preprocessing of the raw data, where anomaly detection is applied, and outliers are filtered out. Then through association rule mining, a broad insight into building's energy behavior is gained from the unlabelled records. The most significant rules from affinity analysis indicate what attributes should be further analyzed in the next steps for classification and regression. Decision tree and k nearest neighbors (K-NN) classification algorithms are implemented for categorizing energy behavior

Table 1 Summary of previous studies in the literature

Article	Machine learning technique	Result's summary description	Model accuracy (%)
Howard et al. [3]	Multilinear Regression	Annual bldg. energy consumptions by end-use and by bldg. function are predicted for residential buildings in NYC, and spatial distributions for those consumptions are shown	86
Hsu [4]	Regression Clustering: 20-fold cross-validation	Cluster-wise regression provides an accurate prediction, but unstable clusters. While K-means gives more stable clusters, but poor predictions in some clusters	94
Kuo et al. [8]	Classification (Decision Tree) Regression Clustering	Combination of 2 bin equal interval data subset and Logistic Model Tree (LMT), EUI presents the highest performance	87
Im et al. [6]	Multilinear regression tenfold cross-validation	Equipment power density resulted to be the most important variable contributing to the electricity consumption	84

per building through three main target variables, i.e.., building energy efficiency grade (based on energy star score); GHGE Intensity; and weather normalized (WN) site EUI. In parallel, support vector regression (SVR) and multilinear regression (MLR) algorithms are applied to quantitatively predict building energy performance for the aforehand mentioned variables, and to identify the most influential predictor attributes among building characteristics such as year built, gross floor area (GFA), location, and energy-related historical data. Ultimately, an example of GIS spatial validation for a specific residential building is illustrated to confirm predicted model results against actual building energy performance behavior.

4 Case Study

Raw datasets used for this study were obtained from the NYC Open Data web-portal. The "Energy and Water Data Disclosure for Local Law 84" datasets, published by the Mayor's Office of Sustainability, include metrics on energy consumption in privately owned buildings [13]. The most recent and robust datasets were collected and merged

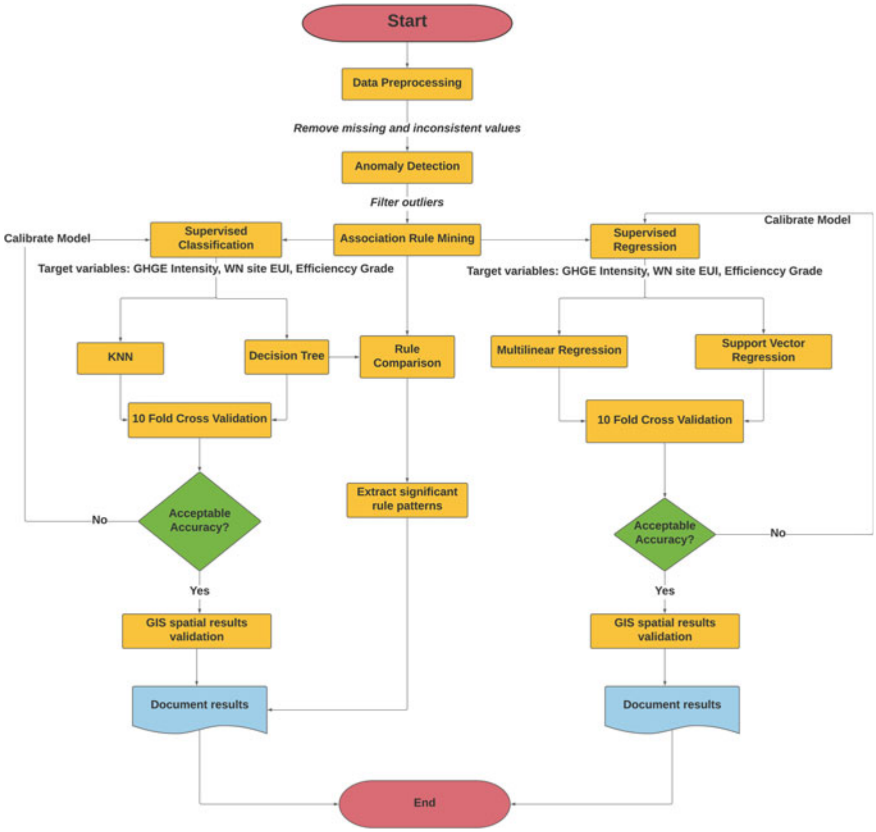

Fig. 1 High-level methodology flowchart

in a single raw dataset to cover a four-years period of data (i.e., 2016–2019) with 85.5 k datapoints and 60 attributes. After feature selection, anomaly detection and outlier removal, the data frame size reduced to 30.3 k building data-points and 23 attributes. The selected attributes include gross floor area; year built; WN site EUI, direct GHGE, indirect GHGE, WN site electricity, WN natural gas use, WN source EUI, latitude, longitude, among others.

The applied supervised and unsupervised processes were modeled and run using RapidMiner Studio software version 9.9 [16]. Three of the major reasons of selecting this tool are the user-friendly interface, the availability of functional modeling operator's library, and the broad visuals that it provides for multivariate modeling.

4.1 Association Analysis

The association rule mining method is applied in the present study to identify relationships among different metrics of energy consumption, GHGE, and building characteristics. In this analysis, the weather normalized attributes consider the yearly weather variation for NYC. Data inconsistencies were discarded using anomaly detection process, and missing values were filtered out. All numerical attributes were discretized based on their quartile statistics to ensure homogeneity of the dataset, (see example details in Table 2). These attributes were then turned into binominal data type to apply FP-Growth algorithm.

Most frequent rules were obtained from the affinity analysis. However, only those rules with minimum support and minimum confidence values greater or equal to the threshold of 20% were kept. The lift measure was also considered to define how interesting the rules are. Finally, the rules containing high WN site EUI, high GHGE, high source EUI, and low efficiency grade of C as their conclusions were mainly analyzed considering that the worst possible building energy performance is bounded by this type of rules. The identification of these associations is valuable to discover the main influencing attributes (premises) contributing to the poor building energy behavior. Table 3 illustrates relevant discovered association rules.

Table 2 Example of statistical quartile-based discretization

Variable	Item discretization	Range
Energy efficiency grade	A	80–100
	B	28–79
	C	0–27
Year built	≥95 years old	1925
	94–58 years old	1926–1962
	≤57 years old	1963–2020
GHGE intensity (CO_2e/ft^2 tons)	Low	0–4.3
	Medium	4.4–6.76
	High	6.77–90
WN Site EUI ($kBtu/ft^2$)	Low	0–69.7
	Medium	69.8–86.4
	High	86.5–1550
WN Source EUI ($kBtu/ft^2$)	Low	0–104.1
	Medium	104.1–125.9
	High	125.9–2055

Table 3 Example of significant discovered associations

Premises	Conclusion	Support	Conf	Lift
Indirect GHGE (CO_2e tons) = High; WN site electricity (kWh) = Low; WN source (kBtu/ ft^2) = High	WN Site EUI (kBtu/ft^2) = High	0.2	0.5	2.0
WN site electricity (kWh) = low; Year built = 94–58 years old	Indirect GHGE (CO_2e tons) = High; Borough = Bronx	0.2	0.3	1.2
Indirect GHGE (CO_2e tons) = High; WN site electricity (kWh) = Low; GFA (ft^2) = Short	Energy Star Score = C	0.3	0.3	1.2
WN site natural gas use (therms) = Medium	Indirect GHGE (CO_2e tons) = High; GFA = Short	0.2	0.6	1.2
GHG intensity (CO_2e tons/ft^2) = Medium; Year built = 94–58 years old	WN Source EUI (kBtu/ft^2) = High	0.2	0.7	1.5

4.2 *Classification*

To train our predictive models, residential buildings were categorized based on a combination of predictor attributes including energy star score, energy-related features, and building characteristics by applying Decision Trees (DT), and KNN classification algorithms. For this study, the discovery of building energy performance patterns is depicted in terms of three main target classification variables WN site energy use intensity (EUI), GHGE, and efficiency grade. Both algorithms are then compared in terms of model performance measures: accuracy, R^2, and error.

4.2.1 Decision Trees (DT)

DT was applied training three different models to predict building energy performance patterns in terms of the main target variables: WN Site EUI; GHGE Intensity, and Efficiency Grade. Information gain ratio was used as the measure for split criterion. Pre-pruning through controlling the maximum depth of trees was applied to avoid model overfitting. DT analysis is a predictive algorithm that maps observations about a certain item to conclusions about its target variables. A DT is composed of a root node (top of the tree), internal nodes where binary split decisions happen if the

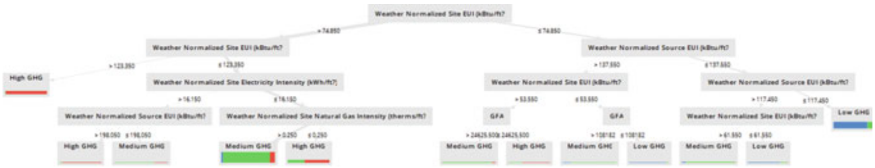

Fig. 2 Decision Tree for GHGE intensity prediction

information gained ratio is greater than the min threshold, and of leaf nodes representing the final classification for the targeted variable or stop nodes in the case of any of the following conditions is met: (1) All records of the dataset share the same target class value; (2) There are no more predictor variables to continue splitting, and (3) There are no more examples left within the predictor variable [23]. Figure 2 shows the obtained DT with a maximum depth of five for predicting GHGE Intensity as Low, Medium, or High for residential buildings in NYC.

After fine-tuning, the WN Site EUI and WN GHGE Intensity models resulted in an accuracy of 81% and 93%, respectively, while the accuracy for the energy efficiency grade model reached 78.1%. Table 4 shows the results from DT classification method. The resulted percentages of corrected predictions and the performance metrics shown in Table 4 were obtained by applying the "Performance" operator to the developed classification models in RapidMiner version 9.9.

Weather and Non-Weather attributes for Site EUI, Source EUI, Natural Gas, and Site Electricity were tested in the developed models. From this, it was found that weather normalized values slightly improved prediction accuracies by 4%, mainly

Table 4 Model performance results

Target attribute	Method	Accuracy %	Root Mean Squared Error (RMSE)	R^2	Kappa factor	Top 3 influential predictor attributes
GHGE Intensity	DT Cross validation (200 folds)	92.4	0.26 ± 0.033	0.85 ± 0.039	0.89	1. WN Site EUI 2. WN Source EUI 3. Gross Floor Area
WN Site EUI	DT Cross Validation (200 folds)	81.03	0.396 ± 0.029	0.75 ± 0.050	0.77	1. WN Source EUI 2. Gross Floor Area 3. Lat-Long Location

Table 5 Model performance results by cross validation

Model/Target variable	Optimal k	Accuracy (%)	Classification Error (%)	RMSE	Squared error	R^2	Kappa factor
Energy efficiency	3	76.90	23.10	0.426	0.182	0.567	0.534
WN Site EUI	9	91.83	8.17	0.243	0.059	0.884	0.850
GHGE Intensity	3	88.32	11.68	0.303	0.092	0.775	0.836

because these values consider the yearly weather variation. Some examples of significant rules inducted from the DT for WN Site EUI, GHGE Intensity, and energy efficiency grade, are:

If GHG Intensity (CO_2e/ft^2 tons) > 3.923 and GHG Intensity (CO_2e/ft^2 tons) > 5.800 and WN source EUI ($kBtu/ft^2$) ≤ 1526.800 and GHG Intensity (CO_2e/ft^2 tons) > 7.874 and WN site electricity (kWh) ≤ 8318154.399 **then High EUI**

If WN Site EUI ($kBtu/ft^2$) ≤ 74.850 and WN Source EUI ($kBtu/ft^2$) > 137.550 and WN Site EUI ($kBtu/ft^2$) > 53.550 and GFA > 24625.500 and Latitude > 1.334 and Latitude ≤ 1.434 **then High GHGE**

If WN Source EUI ($kBtu/ft^2$) > 103.450 and WN Source EUI ($kBtu/ft^2$) > 146.450 and WN Site Electricity (kWh) > 6887.550 and GFA ≤ 7181.500 and Borough = Manhattan **then Low Efficiency Grade (C)**

4.2.2 kNN Classification

Another classification tool used in this study and compared versus the DT is k Nearest Neighbors (kNN). To find the optimal K, three different models were created, one for each independent target variable, i.e., WN Site EUI, GHGE Intensity and Energy Star Score. They were tested with different values of k, from 1 to 9, this to find out the optimal k for each model avoiding overfitting. The optimal K for each model and their results after performing tenfold cross-validation are presented in Table 5.

4.2.3 Results Comparison

As a result of comparing the rules extracted from affinity analysis and the rules obtained from decision tree classification, the following interesting relationships were found: (i) Buildings with high GHGE as their rule's conclusion are frequently associated with both their year of built particularly in the range of 58–95 years, and with the building's borough of Bronx (ii) Buildings with low efficiency grade of C as their rule's conclusion present frequent association patterns with high indirect GHGE, GFA, and building's boroughs of Brooklin and Manhattan (iii) Buildings with high WN site EUI are recurrently associated with the WN site natural gas use and to their high levels of GHG emissions.

Table 6 Classification result's summary

Target variable	Performance measures	DT (Cross validation)	KNN
Energy star score	Accuracy (%)	78.09	76.90
	RMSE	0.428	0.426
	R^2	0.598	0.567
WN site EUI	Accuracy (%)	81.03	91.83
	RMSE	0.34	0.243
	R^2	0.75	0.884
WN GHG intensity	Accuracy (%)	92.4	88.32
	RMSE	0.278	0.303
	R^2	0.86	0.775

The third range of year-built attribute (≤57 years old) resulted in remarkably high range electricity use in the borough of Manhattan. This could be owed to the emerging construction methods after world war II period, for instance, the use of insulation in building envelopes, considerably reduces the body mass of buildings leading to an increasing loss of thermal energy with higher GHGE and higher energy demand. Table 6 shows a comparison summary of the results obtained from DT and KNN classification techniques.

4.3 Regression

The objective of regression modeling in this study was to predict GHGE, WN Site EUI, and energy efficiency grade. Two types of regression methods, multilinear regression and support vector regression were applied to discover the best fitting function for the dataset of this study. In addition, for MLR, "none" and "greedy" feature selection methods; and for SVR, "dot," and "radial" kernel type function were tested. Subsequently, for evaluating the performance of developed models, different methods such as split data, split validation, and cross validation with 10-folds were examined. The base dataset described in Sect. 4, and the dataset from cluster 0 in Sect. 4.3 were used for regression analysis. The analysis results indicated that the trained models based on the base dataset were more robust than those based in cluster 0. Therefore, regression results from cluster 0 are excluded. In parallel, the predictor attributes with the highest level of significance are identified. MLR provides a better fit and more accurate prediction models for GHGE and EUI than SVR. As a result, the SVR results are also excluded from this study. Table 7 summarizes MLR results.

Table 7 Summary of MLR performance results

Target attribute	R^2	Attributes with high level of significance
GHGE intensity	0.955 ± 0.013 (0.956)	– WN Site EUI – WN Site Natural Gas Intensity – WN Source EUI
WN site EUI	0.993 ± 0.001 (0.993)	– WN Source EUI – WN Site Electricity Intensity – Indirect GHGE
Energy efficiency grade	0.605	– Largest Property Use Type – WN Site EUI – Year Built

5 Result's Validation and Discussion

The outcome from affinity analysis allows for the identification of most relevant associations between energy-related attributes and building physical characteristics, while classification and regression techniques enable the discovery of building energy performance patterns. The results from applying DT classification algorithm in previous studies reported an accuracy of 87% for EUI (see Table 1), and for this study resulted in an accuracy of 85.6% for WN Site EUI and 93% for GHGE. This variation in the results is assumed to be attributable mainly to the selection of the city for the study (e.g., Taiwan vs New York), target variables (e.g., GHGE), and predictor attributes (e.g., building gross floor area). Furthermore, the results from applying regression analysis in this study included the identification of the most influential attributes for predicting building energy behavior, which resulted in the following: year built, fuel type, gross floor area, and location. These attributes were identified by their highest level of significance according to the relevance measures of 4 Stars, P value = 0, and highest t-stat.

GIS spatial validation of trained models through georeferenced maps allows tracking of energy behavior patterns over time for any particular residential building based on its building identification number (BIN) attribute [12]. Table 8 shows an

Table 8 Sample of GIS verification of energy performance patterns for a residential building

BIN year built [12]	Measured results by GIS [12]	Predicted classification results	Predicted MLR results
BIN: 1010899 Year Built: 1964	GHGE = 10.57(High)	GHGE = High	GHGE = 11.17 (High)
	Efficiency Grade = 1 (C)	Efficiency Grade = C	Efficiency Grade = 0 (C)
	Site EUI = 260 (High)	WN Site EUI = High	WN Site EUI = 184.7(High)

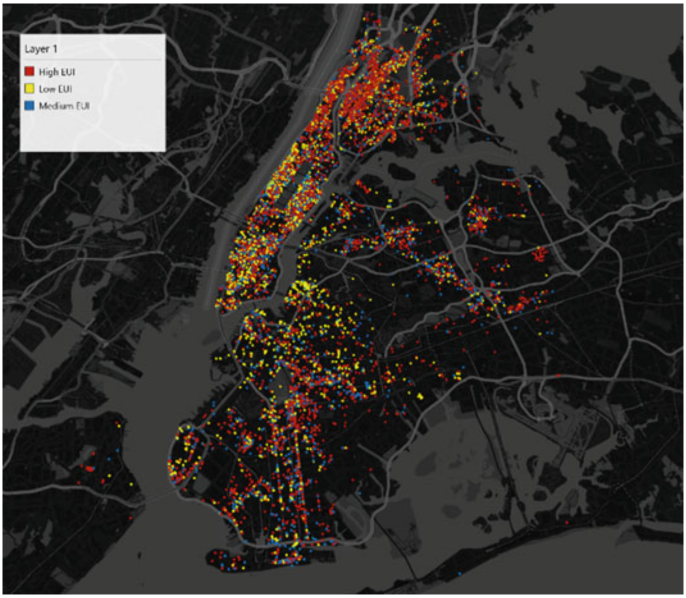

Fig. 3 WN site EUI; red class = high EUI

example of GIS spatial validation of the trained models for a specific residential building in NYC regarding its energy behavior patterns.

According to the GIS spatial analysis of the trained models, the highest proportion of residential buildings with low energy efficiency grades belongs to Manhattan and Bronx boroughs. The number of buildings in the class of High EUI (>86.4 kBtu/ft^2) is higher than those in low and medium classes for the five boroughs of NYC (Fig. 3). Moreover, the heat map shown in Fig. 4 shows a high volume of direct GHGE released to the atmosphere majorly by Bronx and Manhattan. Lastly, in Bronx, there is a greater number of buildings within the high GHGE Intensity class than those in other classes. In general, 52% of the buildings are classified as Medium GHGE Intensity considering the five boroughs of NYC (Fig. 5).

Another interesting observation by looking into the results is that the average GHGE Intensity of whole NYC's residential buildings has not decreased in four years emitting a minimum constant of 4.85 metric tons/ft^2. Therefore, if NYC keeps the same consumption patterns for the upcoming years, then the city will not achieve its goal of reducing 80% of GHG emissions by 2050 unless energy efficiency programs get implemented including the incorporation of green energies and the improvement of its energy distribution system management.

The implicit knowledge of energy consumption characteristics obtained by the referred analysis can be used to (i) provide building owners with accurately predicted energy consumption performance to optimize architectural space, business equipment and operations management; (ii) set thresholds of various key design factors for

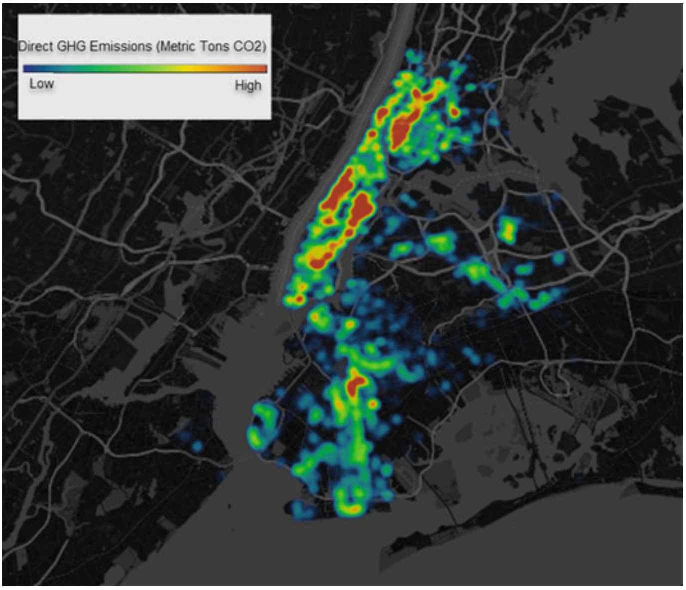

Fig. 4 Heat map of direct GHG emissionsd

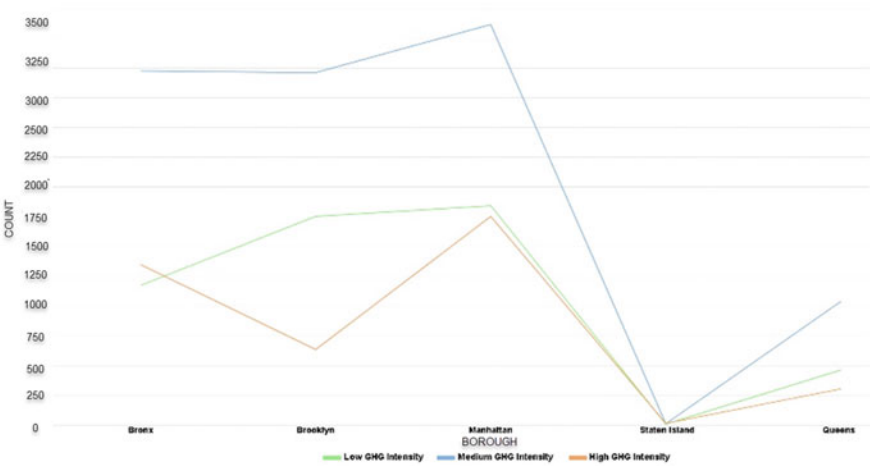

Fig. 5 GHGE intensity by borough low = green; medium = blue; high = orange

city planners; (iii) validate future related prediction models; and (iv). Serve as decision support tool for governments particularly for energy and environment departments to plan and develop carbon emission reduction policies, which can result in energy savings.

6 Conclusions

This paper presents a machine learning approach towards identifying and predicting energy consumption patterns for residential buildings in NYC based on the wide variation of building characteristics, location, and energy-related historical data. These patterns are composed of three main target variables: WN site EUI, GHGE intensity, and energy efficiency grade. The results from association analysis revealed existing relationships among building location, year built and the three referred target variables. On the other hand, classification and regression methods focused on the prediction of energy behavior and pattern discovery for GHGE and WN site EUI. However, due to the lack of more robust information per building such as occupancy behavior, climate change over the years, and type of construction materials, the possibility of reaching higher accuracies for the energy efficiency grade trained models was prevented. It is worth mentioning that for future studies, the inclusion of other building energy-related attributes into the analyzed dataset could significantly improve the performance of the trained models increasing the chances to achieve better predictions for the upcoming thirty years to comply with the goals pursued by NYC and with the commitments made in the Paris agreement [20].

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A Faceted Classification System for Innovation in the Construction Industry

Claire Delarue, Érik A. Poirier, and Daniel Forgues

1 Introduction

Innovation in construction has always been an important issue. While other industries such as aerospace and automotive, have massively invested in innovation to improve their performance, the very nature of the construction sector has made it more difficult to innovate [3]. Accustomed to more traditional methods, construction industry stakeholders have a significant role to play in transforming and modernizing the industry through innovation and deploying technology to perform in the face of labour shortages, international competition and declining productivity [6]. Supporting these stakeholders in the innovation process is critical to ensure its success.

The classification of technology and innovation in the construction industry can help stakeholders navigate the process and inform decision making and action in this area. Successfully developed and deployed, the classification effort should allow industry stakeholders to gain a better understanding of these innovations, help them identify the scope of their impact and improve their competitive advantages through a more thorough understanding of the different elements involved in the innovation process [22]. The classification of innovation can also help guide industry stakeholders towards the resources needed to implement new technologies, products and processes in their business strategy [14]. That being said, the classification of innovation in the construction industry still requires attention as past efforts have not addressed the full breadth and depth of this particular topic [15].

This paper presents the results of a broader research project aimed at investigating the impact of technological innovation on productivity in the construction industry. The purpose of the research presented in this paper was to develop a classification of innovation in construction based on the literature. It was subsequently tested

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S. Walbridge et al. (eds.), *Proceedings of the Canadian Society of Civil Engineering Annual Conference 2021*, Lecture Notes in Civil Engineering 247,
https://doi.org/10.1007/978-981-19-0968-9_2

through a survey sent through two construction associations in Quebec. The proposed classification presents five facets of innovation in construction. Its utility lies in the fact that it supports five complimentary perspectives on a particular innovation, potentially allowing the categorization of innovation and its outcomes.

2 Innovation Classifications

2.1 Characteristics of Classifications in Construction

The notion of classification exists in most scientific fields. Its primary purpose is to summarize and organize knowledge on a subject in a structured manner [1]. Classification brings clarity to the chosen domain by establishing the characteristics and structure with which objects are to be organized [9]. In the literature, the classification of technologies in construction has existed for several decades. Research teams refer to one or more ways of grouping technologies, but most focus on only one dimension in their work.

As far as terminology is concerned, the following definitions are considered, as illustrated in Fig. 1:

- The level is a rank in the classification in its hierarchical system. Level 0 corresponds to the root of the classification and the last level contains what needs to be classified. According to the hierarchical system of the classification, a level can contain one or more categories, as well as the elements specific to these categories.
- A category is a dimension used to classify. It can also be named attribute. It is a subdivision criterion corresponding to a characteristic of what is to be classified.
- A category is composed of several elements or classes. According to the hierarchy of the classification, one can speak of sub-elements or sub-classes for the elements of the categories of the following levels.
- The entities to be classified, here innovations, are called objects in the classification. They have points in common with the elements and sub-elements with which they are affiliated.

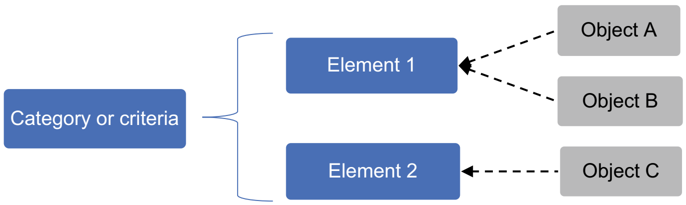

Fig. 1 Terminology of a category in a classification

In construction, classifications generally have only one category in the scientific literature, but several criteria are used in a single classification when it has practical use in industry. For instance, widely used classification systems in the North American construction industry are OmniClass, MasterFormat and UniFormat (both the latter existing under a certain form within the former). Many others exist all over the world and all of them have different purposes, structures, and properties, so they are often compared in the literature for adapted use [1, 11]. Among the most widespread structures in multidimensional classifications, hierarchical and faceted systems stand out. The first one imposes a subjective vertical hierarchy between criteria whereas the second considers a horizontal hierarchy between them, called facets. It is possible to mix these two structures as a mixed system, as it combines several types of hierarchy into one system. OmniClass and UniClass classifications are an example of this, as they are faceted classifications that have some similarities in their structure with the hierarchical classification [11]. Generally, these three types of classification systems are applied in the construction sector. When several criteria are considered in the creation of a classification, it is important to consider how to organize the selected category or categories as subdivision criteria.

By comparing hierarchical and faceted systems through Fig. 2, several limitations can be highlighted by the way that objects are included in these systems. In this figure, the characteristics of the triangular object are part of the elements present in the criteria defined in the two classification systems. It integrates easily in both models, but it remains however easier to find in the faceted classification, because the

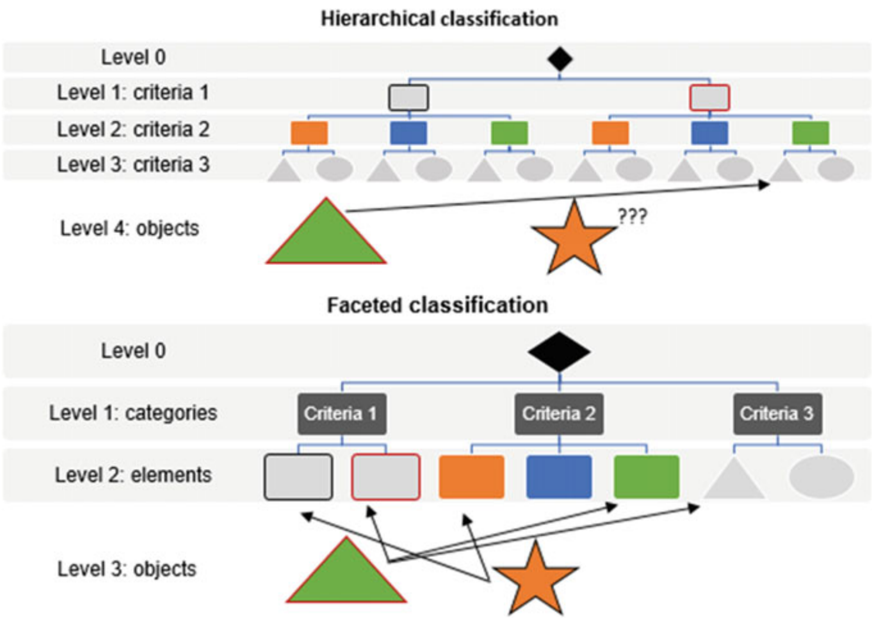

Fig. 2 Principles for categorizing hierarchical and faceted classifications

object integrates several times. The star, on the other hand, is an object whose a part of the characteristics is found in the criteria elements of the classifications, because the star shape is missing in the elements. The structure of the hierarchical system does not allow to classify this object, however legitimate, because of the organization of its criteria and the absence of exceptions. The occurrence of an element that has not been foreseen in a classification criterion hinders its classification. The faceted system, on the other hand, makes it possible to integrate a single object into several categories, even if a characteristic of the object is not present in the elements or criteria. This allows the second object to be integrated into the system and thus makes the classification more complete and accurate. Moreover, a faceted system is more suitable for adding new classes (extensibility) without changing the existing structure (stability), two crucial aspects in designing an effective classification [11].

In the case of innovation, the objects to be classified will continue to evolve over time, thus extending the choice of elements for each criterion, which makes it relevant in this case. This system, originally used in library and information science, allows a concise approach that can cover different points of view in a single structure [23] and has expanded into other areas over the years.

2.2 *Classifying Technologies and Innovations in the Construction Industry*

The dimensions for classifying innovations are multiple and various, especially in construction. Table 1 describes the various facets identified in the literature on innovations and technologies in the construction industry, most of which involve the development of frameworks, models and classifications on this topic. Some of the terms used by the authors are different, but in fact correspond to similar dimensions

Table 1 Facets of classification found in the literature review

Facet	Authors
Impact/Benefit	Lim and Ofori [14], Noktehdan et al. [17]
Location	Blanco et al. [2]
Application/Service/Business function	Blanco et al. [2], Nasir [16], Jung et al. [13]
Discipline/Construction category	Tatum [22], Ferguson [8]
Project phase/Asset life cycle	Jung and Gibson [12], Ferguson [8], Noktehdan et al. [18]
Degree of disruption	Slaughter [21], Noktehdan et al. [17]
Form of innovation	Goodrum et al. [10], Tatum [22], Reichstein [20], Noktehdan et al. [17]
Type of innovation	Dodgson et al. [7], Ozorhon et al. [19]
Input-process-output (IPO) perspective	Crossan and Apaydin [4], Goodrum et al. [10], Tatum [22], Ozorhon et al. [19]

when a closer look is taken at the elements that make them up. As a result, these categories complement each other and can then be grouped together to obtain a more accurate dimension.

The facet concerning impact brings together the different effects that innovations can have on firms and projects. Lim and Ofori [14] identify, for example, the reduction in project costs for the entrepreneur, the competitive advantage or the client's voluntary financing of the innovation whereas Noktehdan et al. [17] put forward performance indicators. The location of innovation can be physical or symbolic, especially for digital technologies. Business functions relate to the internal activities of companies during a project such as project and resource management, planning or estimating. Discipline corresponds to the different branches of the stakeholders intervening on the project. This facet is also found in classifications commonly used in construction such as Uniclass or Omniclass. The project phase or asset lifecycle includes the different stages of a construction project. The degree of disruption caused by the implementation of innovation, according to Slaughter [21], corresponds to the way in which the innovation will theoretically impact its environment, ranging from incremental innovation (small change) to radical innovation (large change). The form of the innovation deals with the physical or abstract form it may take. Some authors have also classified by type of innovation. However, this facet is more specific to the studies that use it and the authors find it very difficult to complement each other, as the points of view are so divergent. Finally, innovations can be classified as either an input, a process, or an output (IPO). Innovation is usually considered as an input or an output [19], but can also be identified as a process [4].

Among all these facets, some are specific to the theoretical aspect of the innovation, such as the degree of disruption, or to its practical aspect, such as the phase of the project, the discipline or the impact. In the context of this study, emphasis is put on more practical facets as they are more useful for construction industry stakeholders. In addition, it is important that all facets be clear and understandable, as the lack of clarity could potentially lead to misclassification. For example, type of innovation, as a facet, has not garnered consensus among researchers. It is use as a facet can therefore cause confusion and undermine the classification effort. Of the multiple studies reviewed, there remains a lack of facetted classification which supports a practical view of innovation in construction.

3 Methodology

The classification effort discussed in this paper is part of a broader study aimed at understanding the impact of innovation on productivity in the construction industry. Portions of the study are explained in Delarue [5]. For the purpose of the overarching study, the research team had to develop a classification that could support a more structured investigation and analysis of innovation in the construction industry. As previously mentioned, a thorough review of the literature and state-of-the-art highlighted an absence of such a classification. It was therefore determined that a facetted classification be developed for the purpose of the study.

To develop the classification, the research team first identified the different types and facets of innovation that have been developed in the literature (ref. Table 1). In developing the classification, a consensus rapidly formed around choosing a facetted approach instead of a hierarchical one, for the reasons discussed above. Indeed, one of the main concerns with the classification being developed was around flexibility and adaptability as it contended with a rapidly evolving field. The choice of facet was therefore based on scientific and industrial literature. Characteristics and industrial aspects of innovation are considered. Elements of each facet were then developed.

To evaluate, expand and validate the classification and its practicality, a survey was conducted over a three-month period in late 2020. Each respondent of the survey was asked to list up to tree innovations that had been implemented in their firm within the past five years. The classification was used to identify and categorize these innovations, therefore providing ample data and opportunity to develop and test its components. The 161 compiled responses to the survey, which targeted general and specialized contractors in Quebec's construction sector, resulted in a total of 100 innovations. The categorization is done for each facet chosen in the development of the classification.

4 Results

4.1 Development of the Classification

Among the various dimensions identified in the literature, some complement each other, and others are less relevant to this project. It should also be considered that the number of final facets must be balanced to be of both practical and academic relevance. With this in mind, 5 facets of technological innovation were identified and developed in the study. These are illustrated with their constituent elements in Fig. 3:

- The **life cycle of the asset** makes it possible to classify innovations and technologies according to the stage of the life cycle of the built asset. Some technologies are only used at specific stages of the project. For instance, on-site technologies such as drones, laser scanners or robots will be more often present in the construction phase. The planning period will have more information technologies because it is an early stage in the project. Finally, it is also possible to find certain technologies and innovations that cover the entire lifecycle of an asset such as building information modeling (BIM) and artificial intelligence, as they are integrated into many practices or innovations.
- The **discipline** lists the different sectors in which the innovation can be applied. Some innovations have been designed for particular disciplines while others can

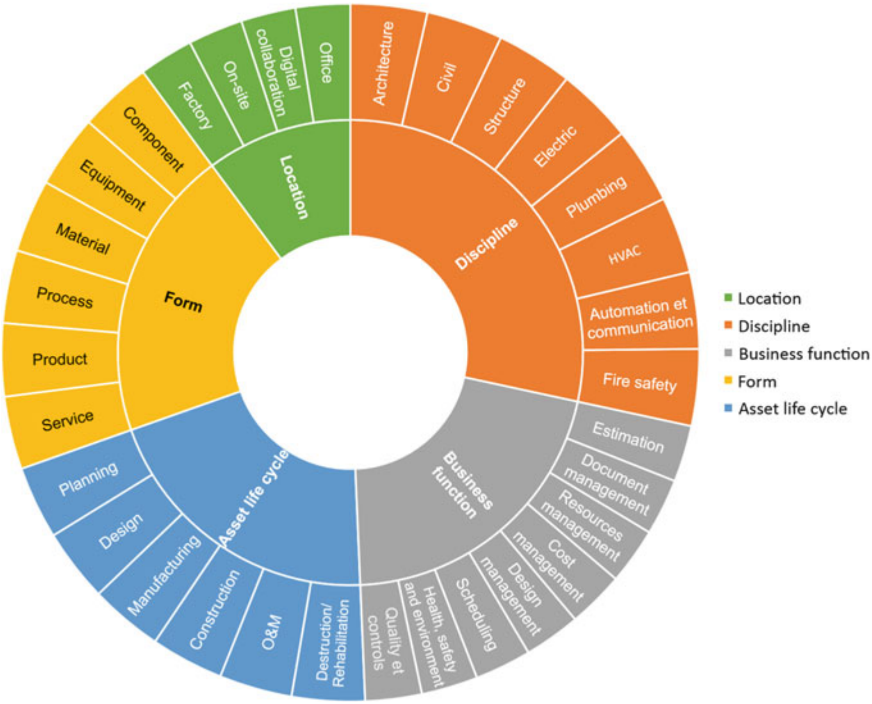

Fig. 3 Faceted classification of innovation

be used by all stakeholders involved in a project or over an asset's lifecycle. This is particularly the case for specialized equipment which can be suitable for a specific trade. Furthermore, by listing by discipline, it is possible to draw inspiration from technologies specific to certain trades in order to adapt them to other trades to obtain similar benefits such as safety, quality and productivity, in the same way as construction innovations inspired by other sectors of activity.

– The **form** concerns the physical or symbolic dimension of the innovation. This facet makes it possible to identify the format that the technology used in a project can take. It can be material, such as portable technologies and machines, or immaterial, such as software or innovative processes. In this category, innovations are also considered to be components of other technologies or tools. This may be a part that improves an existing piece of equipment, but it may also be the driver of software created for a specific computer use.
– The **business function** classifies innovations according to the general activities of the company. The elements included in this facet are internal activities that have an impact on the firm or on projects. They generally concern the concepts used in project management, with activities related to costs, time or quality. The technologies in this category generally help firms to improve internal or project related aspects.

– The **location** refers to the physical or symbolic location from innovation to use. This dimension includes the main locations of the technology. It can be physically present on the project site, such as equipment, materials or portable technologies, or on the fabrication plants as innovative process of fabrication or specific machines. It can also have a symbolic location, whether it is in company offices, with digital and management technologies, or in a digital cloud via servers for digital collaboration and sharing tools.

Following the principle of faceted classification, not every innovation is necessarily present in all facets, but it can also correspond to several elements of the same dimension. The absence of one facet may be justified by the fact that it could be integrated into all the elements that compose it, or that the innovation does not apply to a particular facet. Innovations that can be integrated several times into one facet can have versatile uses and be presented in different applications.

4.2 Practical Assessment of the Classification

As mentioned, the proposed classification was validated through the survey responses obtained in the context of the broader study on innovation and productivity. In order to validate the classification, survey respondents were asked about three technologies used in their projects and then classified them. Naturally, as the survey was mainly directed towards general and specialized contractors, the lifecycle facet concerned construction. In all, the research team was able to list 59 different technologies, the most commonly cited of which were BIM, laser or 3D scanning, GPS, 3D modeling and collaborative applications. Figure 4 illustrate the frequency of innovation per facet identified in the survey.

The figures above were developed from the innovations identified and classified by the research team. Table 2 lists these innovations and their categorization with four of the five facets. The asset life cycle was not represented because the survey was mainly focused on contractors' technologies, who are involved in the construction phase of projects. The term "multiple" has been used several times when several elements of the same facet characterized the innovation, as a simplification of the characterization. It is easy to notice that it was mostly used for the Discipline facet. Indeed, as mentioned in the development of the classification, a technology can be integrated into several elements. For example, an innovation can be multiform and this is what Noktehdan et al. [17] have detailed some elements of this facet in their classification. The same is true for localization with mobile technologies and for business functions. In itself, multiple elements are as much an indication for the characterization of innovations as the others, particularly with regard to the discipline, which makes it possible to distinguish between general technologies and those specific to a profession.

Form and location facets concern innovation aspects and were assimilated easily to the elements of the classification. In contrast, industry-specific facets such as business

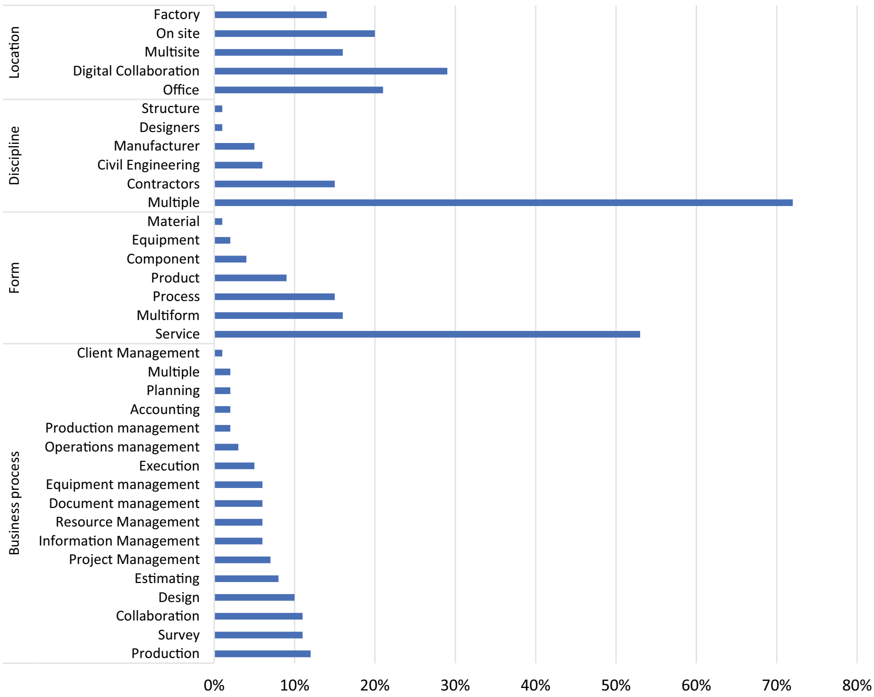

Fig. 4 Frequency of innovation per facet (n = 100)

function and discipline have had a more subjective and complex categorization. In this case, elements that were not in the initial classification had to be added to improve the classification of the list of innovations. Some classification management functions were used, but other concepts, such as accounting, client or operations management, were missing. Among the elements added for business functions, some are closely related to the project phase such as the planning, design, manufacturing and execution phases, without generating many multiple elements. As far as discipline is concerned, it is more the trades that have been added to the initial elements.

5 Discussion and Conclusion

The aim of this research was to allow construction actors to have a better understanding of innovations through the development of a classification. Indeed, this paper presented a faceted classification composed of five dimensions which correspond to innovation features or industrial aspects of the construction sector: location of the innovation, its form, business function of companies, the discipline of applicability and the phase of the project in its asset life cycle. Classified innovations

Table 2 Categorization of the innovations from the survey

Innovation	Form	Location	Business function	Discipline
360° and 3D camera ground survey	Equipment	On site	Surveying	Multiple
3D and laser scan	Multiple	On site	Surveying	Multiple
3D Modeling	Service	Digital collaboration	Design	Multiple
3D Plans	Service	Multiple	Design	Multiple
Accounting software	Service	Office	Accounting	Multiple
Advanced networking technology	Service	Digital collaboration	Collaboration	Multiple
Advanced or integrated estimating software	Service	Office	Estimation	Multiple
Ammonia injection system for industrial chimneys	Component	Factory	Production	Fabricant
Asphalt plants automation	Multiple	Factory	Production	Civil
Bidding Process Automation	Service	Office	Estimation	Multiple
BIM	Multiple	Digital collaboration	Information management	Multiple
Calibration and measurement tools for production plants	Service	Factory	Production	Fabricant
Cloud computing	Service	Digital collaboration	Document management	Multiple
Cloud-based management software with project tracking	Service	Digital collaboration	Operations management	Multiple
Collaborative project management software	Service	Digital collaboration	Project management	Multiple
Computerization of Work Planning	Process	Office	Resource management	Multiple
Computerized survey tools	Service	Multiple	Estimation	Multiple
Construction site monitoring software	Service	Multiple	Project management	Contractors
CRM	Service	Office	Clients management	Multiple
Daily report on touchpad	Service	Multiple	Project management	Contractors
Design software	Service	Office	Design	Multiple

(continued)

Table 2 (continued)

Innovation	Form	Location	Business function	Discipline
Digital design	Service	Digital collaboration	Design	Multiple
Digital timesheets	Service	On site	Resource management	Multiple
Document management software	Service	Office	Document management	Multiple
Drone	Product	On site	Surveying	Multiple
Equipment and material tracking tool	Service	Multiple	Equipment management	Contractors
Equipment for monolithic manholes and grommets	Equipment	On site	Production	Civil
Equipment maintenance	Process	Multiple	Equipment management	Contractors
ERP	Service	Office	Resource management	Multiple
Factory-Integrated Culvert Fish Passes	Component	Factory	Production	Civil
GPS	Multiple	On site	Equipment management	Multiple
Grader with joystick and 4 wheels steering	Product	On site	Execution	Civil
Heat recovery	Process	Factory	Production	Fabricant
High-performance filters to meet NESHAP standards	Component	Factory	Execution	Fabricant
Implementation of a new accounting system	Process	Office	Accounting	Multiple
Integration of job site tasks into a single data collection	Process	Office	Resource management	Multiple
Lean construction	Process	Multiple	Production management	Multiple
Machine guidance for excavator or ram	Component	On site	Execution	Civil
Management of tools and connected tools	Product	On site	Equipment management	Contractors
Mobile pointing application	Service	Multiple	Resource management	Contractors
Modularization workshop	Product	Factory	Production	Contractors

(continued)

Table 2 (continued)

Innovation	Form	Location	Business function	Discipline
More efficient computer system	Multiple	Office	Multiple	Multiple
OCR	Service	Office	Document management	Multiple
Off-site manufacturing	Process	Factory	Production	Contractors
Operations and Management Software	Service	Digital collaboration	Operations management	Multiple
Pavements with electric system instead of propane	Product	On site	Execution	Civil
Performance tracking tools	Service	Multiple	Project management	Multiple
Precast concrete	Material	Factory	Production	Structure
Preconstruction	Process	Factory	Planning	Contractors
Preconstruction in Design collaboration	Process	Digital collaboration	Design	Contractors
Prefabrication	Process	Factory	Production	Contractors
Project monitoring software	Service	Multiple	Project management	Multiple
Quantity calculation software	Service	Multiple	Estimation	Multiple
Robot	Product	Multiple	Execution	Contractors
Shared or participatory platform	Service	Digital collaboration	Collaboration	Multiple
Takeoff software	Service	Office	Estimation	Multiple
Touchpad	Product	Multiple	Information management	Multiple
Valorization of rejects in manufacturing processes	Process	Factory	Production	Fabricant
Web transition with ERP	Process	Office	Multiple	Multiple

could be integrated in each classification and correspond to several elements of a same dimension. In a practical assessment, the categorization according to business functions and disciplines shown that these facets needed to be deepened in order to be properly associated with actual construction technologies. The structure of the model allows an easy extensibility and reorganization of the elements keeping a great stability.

The model developed has made possible to undertake an unusual way of classifying innovations, particularly in construction. The facets and their elements have been developed, considering the use of classification by stakeholders, which is little applied in the models in the current literature. Moreover, most of the classifications on this theme are too old to be used as it is in the current technological context.

Among the limitations of this research, the notion of multiple elements can be cited. Although necessary in the categorization, it has to be detailed by the actual elements of the classification and by those add in a future work by consolidation of the current work. By the same occasion, a differentiation could also be done for the innovations which apply to all or none of the elements of a facet, a point that was not considered in the assessment of the study. Future research could apply the present model to a practical use, using facets and elements as filters in the research of stakeholders in the implementation of innovations in the construction projects.

Acknowledgements This paper is produced bases on a research project in collaboration with the Association de la construction du Québec (ACQ) and the Association des constructeurs de routes et grands travaux du Québec (ACRGTQ). The work presented was partly financed by a grant from the organism Mitacs.

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Construction Innovation in the Province of Quebec: Barriers, Drivers, Enablers and Impact

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1 Introduction

The construction industry is a sector with significant economic weight at the global, national and provincial levels. In fact, relative capital expenditures represented 46.3 billion Canadian dollars in 2017, which corresponds to 12% of Quebec's GDP [6]. However, productivity studies agree that construction productivity rates have significant differences with those of other sectors [12, 19]. For instance, manufacturing or aerospace industries have indeed seen their growth and productivity increase considerably in recent decades, thanks to the investments in research and development (R&D) and the implementation of innovations used for the modernization of production lines and the digitization of their sector.

In comparison with other economic sectors, construction has traditionally been viewed as not innovative [11]. While some blame the lack of business experience and investment [16] or the lack of clear benefits from technologies [14], Barbosa and al., for the Mckinsey Institute (2017), state that the biggest barriers to the adoption of innovations in construction companies are underinvestment in technologies, especially IT, in addition to the lack of R&D processes. In fact, construction sector is one of the less digitalized and new investments models for technologies are required to enhance project performance [15]. In the construction industry, only 25% of companies have defined a strategy around digital and only 9% declare to be ready for digitization [4]. Moreover, investment in research corresponds to less than 1% of revenues for most companies, compared to 3.5–4.5% for the automotive and aerospace sectors [1]. This fact can be explained by lower margins in the construction sector on projects compared to other industries.

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S. Walbridge et al. (eds.), *Proceedings of the Canadian Society of Civil Engineering Annual Conference 2021*, Lecture Notes in Civil Engineering 247,
https://doi.org/10.1007/978-981-19-0968-9_3

The province of Quebec's construction industry faces many of the same issues as its Canadian counterparts: the lack of manpower, the globalization of the sector and sustainability concerns [3]. In this light, most agree that innovation across the project lifecycle and supply chain are critical in increasing the industry's productivity and performance [7]. There remains however, a significant gap between understanding the potential of innovation from a macro level and understanding the drivers and barriers of innovation in the field. Moreover, innovation is a broad topic which manifests itself in many ways. It is therefore relevant to understand its impacts and dynamics in an effort to take the appropriate measures to drive its adoption in the construction industry.

The study presented in this paper aimed to answer the following question: What are the dynamics of innovation in the Quebec construction industry? What impacts do they have, particularly on construction site productivity? The main objective of the study was to identify the characteristics of innovation in construction, the factors impacting its implementation and ways to improve its implementation in Quebec. Moreover, the perceived impact of innovation, specifically on productivity was measured. The study presented in this paper is part of a larger research project investigating the impact of technological innovation on productivity and construction performance. For this paper, the context and the dynamics of innovation in the Quebec construction industry are identified. The key drivers and barriers to innovation and its impact are then investigated. Findings reflect the well documented barriers to innovation, but also highlight the lack of support that other sectors benefit from in terms of subsidies and accompaniment. For the companies that have implemented innovation, a majority have reaped considerable benefits in terms of, among others, productivity increase. However, questions still abound on how to capture and measure this impact.

2 Review of Construction Innovation

2.1 Features of Innovation

The notion of innovation can be interpreted in different ways according to the sector in which it is deployed. The construction industry has well known characteristics, such as temporary projects involving several multidisciplinary stakeholders and finished products that have longer lifespan than most other sectors. Due to these characteristics, it would be logical to state that the features of innovation are different from other sectors. However, as with other sectors, technological transformation and innovation remain crucial in construction. Ottinger et al. [13] admit that "Technology is a dominant theme as it continues to reshape conventional property uses, while transforming the back office and construction supply chain" (p.7).

In current scientific literature, there exists to no universal definition of innovation. In fact, innovation remains a complex and multifaceted concept. Some consensus exists around the fact that innovation can be described as a process, a product or a service, among others [8, 14]. Among these different characterizations, Ozorhon and al. [14] consider technological innovation to be new or a considerable improvement of existing technology. They linked it to improved business practices, workplace restructuring, and reconfiguring of external relationships. On the other hand, Kogabayev and Maziliauskas [8] describe technical innovation as "the knowledge of components, linkages between components, methods, processes and techniques that go into a product or service" (p. 64). Finally, Xue et al. [20] recognize three levels that reflect innovation in construction, namely, sector, project and company. Innovation in construction cannot be viewed solely as technologies for manufacturing as the industry has both a manufacturing and a service aspect.

Building on these different perspectives, and for the purpose of the research project, technological innovation is defined as any new (recent) or significantly improved product, service or process as compared to existing technology, that creates opportunities to improve factors such as production, speed of execution, sustainability, safety, etc. on construction sites. Moreover, technological innovation can be implemented on the construction site, remotely in the company's facilities or elsewhere.

2.2 Dynamics of Construction Innovation

The literature considers three categories of elements that influence the integration of innovation into a project: drivers, barriers or enablers. They act positively or negatively on organizations, companies and construction projects. The work of Ozorhon and al [14] identifies and evaluates the impact of drivers, barriers or enablers in the implementation of construction innovations, according to the results of a survey of construction actors in Turkey. Despite the lack of details on the proportion of respondents and the focus on the Turkish industry, their research on these factors allows us to better understand how innovation is implemented and what are the potential stakes.

Drivers of innovation correspond to the elements that would motivate companies or individuals to implement innovation on a project. There is a growing body of knowledge about the role of innovation drivers by considering the client [11], the contractor [10] or the supplier in association with market demand [16] as direct causes. Overall, the literature regularly discusses the role of the client as a driver, but no consensus has emerged from these discussions in recent years due to the lack of concrete studies on the subject. Table 1 summarizes several key drivers of innovation in construction found in the literature.

Obstacles or barriers to innovation are the issues and risks that stakeholders may encounter when implementing an innovation, and which may influence their decision-making. Several barriers are listed in Table 2. Barriers to innovation directly concern the core business, construction projects and market influence. Chowdhury et al.

Table 1 Drivers of innovation in construction sector

Drivers	Details	Authors
Environment and Sustainability	Use of sustainable construction techniques, reduction of environmental impacts and construction of sustainable buildings	Ozorhon et al. [14]
Design trends	Technical capabilities, market demands, opportunities	Ozorhon et al. [14] Reichtein et al. [16]
Project Performance Improvement	More success in terms of time, cost, quality and customer satisfaction	Ozorhon et al. [14] Chowdhury et al. [5] Lim and Ofori [10]
Technological developments	Use of ICTs and technological improvements	Ozorhon et al. [14]
Client requirements	Demands for higher standards in terms of time, cost, quality or performance	Ozorhon et al. [14] Loosemore and Richard [11]
Competition level	Demands for higher standards in terms of time, cost, quality or performance	Ozorhon et al. [14] Chowdhury et al. [5] Lim and Ofori [10]
Regulations and legislations	Improved performance standards	Ozorhon et al. [14]
Corporate Responsibility	Internal process and CSR strategy for better innovation performance and increase customer satisfaction and corporate image	Ozorhon et al. [14] Lim and Ofori [10]

[5] identify categories of barriers to innovation on technological, organizational, financial, psychological, governmental and procedural levels.

Finally, facilitators are elements that help overcome the challenges and obstacles that can arise when implementing innovations in construction projects, as detailed in Table 3. Collaboration in projects and guidance on innovation are the facilitators most often mentioned in the literature. However, the study by Ozorhon et al. [14] conclude that training policy and reward programs have a significant impact. Leadership remains a key enabler also. One key takeaway from this exercise is that there is no consensus on which facilitators has the greatest impact.

3 Methodology

The aim of this research was to understand the dynamics of innovation in the Quebec construction industry, with a focus on its impact on construction productivity. To do so, a survey was designed and distributed to construction actors across the province to take stock of the state of innovation in construction in Quebec. Data collection

Table 2 Barriers of innovation in construction sector

Barriers	Details	Authors
Lack of financial resources	Insufficient or unavailable resources for innovation	Ozorhon et al. [14] Kulatunga et al. [9] Chowdhury et al. [5] Reichtein et al. [16]
Temporary nature of projects	Participation of several teams on the short term or at different times. Difficult collaboration	Ozorhon et al. [14] Xue et al. [20]
Lack of experience and qualified staff	Absence of innovation director, technology managers, R&D sector managers, innovation training. Failure to take technology into account in recruitment	Ozorhon et al. [14] Tatum [18] Barbosa et al. [2] Reichtein et al. [16]
Lack of clear benefits or late return on investment	Lack of clear or quick benefits	Ozorhon et al. [14]
Unsupportive organizational culture	Reluctance to change, strategies not conducive to innovation, little management in the evolution of technologies	Ozorhon et al. [14] Kulatunga et al. [9] Tatum [18] Barbosa et al. [2]
Time constraints	In introducing new ideas and testing new technologies	Ozorhon et al. [14] Salter and Gann [17]
Contractual and legal aspects	Choice of companies with the lowest bidder, contractual constraints. Standards and regulations	Kulatunga et al. [9] Tatum [18] Reichtein et al. [16]
Lack of clients' requirements	Client unsure, unprepared or distrustful of innovation	Loosemore and Richard [11]
Poor digitalization in construction sector	Low investment in digital. Neglecting the potential of computer science in construction	Barbosa et al. [2]
Fear of innovation risk	Risks of counter-productive innovations, undervalued costs, poorly integrated processes, poorly evaluated benefits	Barbosa et al. [2] Loosemore and Richard [11]

took place between September 2020 to February 2021. A total of 280 responses were collected of which 161 were compiled. The response time varied between 5 and 15 min.

The target audience for the survey was general and specialized contractors. The respondents were questioned on the drivers, facilitators and barriers to innovation in their companies and on their projects. They were also asked about their perceptions on the level of support for innovation that is available in Quebec. Finally, they were asked to list specific innovations and technologies and discuss their impacts on project

Table 3 Enablers of innovation in construction sector

Enablers	Details	Authors
Cooperation between project actors	Cooperative environment, coordination and integration of companies	Ozorhon et al. [14] Kulatunga et al. [9] Loosemore and Richard [11]
Early contractors' involvement	Especially in the design phases	Ozorhon et al. [14] Loosemore and Richard [11]
Innovation Award Program	Recognition of efforts and personnel, promotion of innovation, employee involvement. Competitions to promote R&D	Ozorhon et al. [14] Barbosa et al. [2]
Stakeholder engagement	Alignment of motivations and interests. Partnerships with suppliers	Ozorhon et al. [14] Barbosa and al., 2017
Knowledge management	Retention and dissemination of ideas, resources and skills within the company and with stakeholders	Ozorhon et al. [14] Kulatunga et al. [9]
Leadership	Formation of team spirit, vision and goals	Ozorhon et al. [14] Xue et al. [20] Loosemore and Richard [11]
Training policy	Staff training on innovation and its use, internship and field learning	Ozorhon et al. [14]

and organizational outcomes. As such, the survey was structured in 4 main steps, namely:

- General information about the company and the respondent allowed the research team to identify the respondents profiles in relation to innovation in construction.
- Questions on internal processes for the implementation and adoption of technological innovations. Among them were questions around respondents' opinion on their interest in innovation and on the external support they receive for their technological implementation. In addition, respondents answered questions about their use and management of innovations.
- Data on the technologies implemented in companies and on their projects. This included the objectives driving implementation, the adoption rate and the fulfilment of the respondents' expectations. In this section, the respondent had the opportunity to report up to three technologies/innovations implemented in their company.
- Impacts of the technologies implemented on projects and companies. Each listed technology/innovation was then discussed by the respondent in terms of specific indicators such as productivity the return on investment.

Respondents that declared not to use technologies in their projects, they will be able to justify the reasons for not using them and will then be directed towards the end of the survey. The complete questionnaire consisted in 53 questions. The survey was published from respective websites of the two construction associations in Quebec, their newsletters, and their social media accounts.

4 Data Analysis

4.1 Profile of Respondents

The sample was composed at 79% of contractors, of which general 52% were general contractors, 27% were specialized contractors and 12% were suppliers. The rest of the respondents were composed of architecture and engineering firm and manufacturers.

The majority of responding companies had more than 50 employees, with 28% of respondents having between 101 and 500 employees. As far as revenue, a majority made more than 5 million dollars, with 29% declaring revenues between 5 and 25 million dollars and 22% between 50 and 250 million.

All construction sectors were represented, with the majority focused in the civil, industrial, commercial, and institutional sectors. Finally, 46% of respondents declared working everywhere in the province, whereas 40% were focused within a specific area, mainly Montérégie (10,5%), Montreal (10,1%), National capital region (9,2%), Estrie (9,2%) and Laval (7,1%). 15% of respondents declared conducting business outside of the province.

4.2 Innovation in the Quebec Construction Industry

Based on the definition provided above, 77% of respondents indicated a strong or very strong interest in innovation and the use of new technologies in their projects. By cross-referencing this data with the profile of respondents, the types of companies which were the most interested in innovation are suppliers (84% total for a strong (16%) or very strong (68%) interest), general contractors (84% total for a strong (38%) or very strong (46%) interest) and manufacturers (72% total for a strong (29%) or very strong (43%) interest). The rest of the panel, especially specialized contractors, seemed more hesitant about innovations and the implementation of new technologies. Companies with revenues higher than 50 million dollars were those which showed the most interest in innovation. On the other hand, companies which made less than 1 million were the least likely to innovate. This confirms a certain tendency for large corporations to be more interested in innovation. In the same manner, the results show a similar trend according to the size of the companies. In fact, companies with more than 100 employees showed a greater interest in innovation.

Delving deeper into the innovation process, 68% of respondents declared having already used one or more innovations on their projects. Of these respondents having implemented innovation, 55% indicated having at least one person responsible for innovation and its implementation within their organization. Moreover, the larger companies (more than 100 employees) have implemented one or more technological innovations in a strong majority. Indeed, 87% these larger companies had implemented one or more innovations against 56% of companies with less than 100 employees. With regards to revenue, companies earning more than 25 million dollars implement innovations in a higher proportion (82%) than those with lower revenues (54%). When considering the rate of implementation of technological innovations by sector, no one sector stands out as being "more innovative" than another. It can be explained by the fact that the same company may operate in several sectors, which may explain the small gap between the different sectors. According to the company type, the innovation rate is lowest among specialized contractors, while a strong majority of general contractors (68%) have implemented one or more innovations within their company or project. Finally, the 3 regions of the Greater Montreal area (Laval, Montérégie, and Montreal) were seen to have the highest response rate and show a high rate of implementation of innovation.

Moving on to the dynamics of innovation in construction in Quebec, respondents were asked to indicate their agreement with the following two statements on a scale from 1 to 5:

- Statement 01: External and government assistance is sufficient to allow construction companies to develop technologies in their projects.
- Statement 02: The company knows where to turn for help or advice in implementing the technology.

For the first statement, 56% of the panel showed a moderate or strong disagreement, considering that external or government assistance is insufficient to support the implementation of technologies or innovation in their projects. Likewise, regarding the second statement, 44% of respondents expressed moderate or strong disagreement with the statement whereas 27% had a neutral opinion. Delving a bit deeper into this statement, companies with more than 50 employees seem to know where to turn for support in their innovation and technology implementation process. However, no link was found for these companies between the second statement and the appointment of a person responsible for innovation.

4.3 Factors Influencing the Implementation of Innovation in Companies

The survey drew on the literature review to identify the most important factors in the implementation of innovation. For firms that did not implement innovation (32% of the total sample), the survey sought to identify the factors influencing this

Table 4 Barriers to innovation according to the survey (N = 52)

Barriers	Percent (%)	Barriers	Percent (%)
Lack of experience and qualified staff	16	Unsuitable internal structure of the firm	6
Time constraints	14	The company does not know how to do it	6
Lack of clear benefits for the firm	12	Adverse regulatory environment	6
Unfavourable contractual context	11	Insufficient technological maturity	5
Lack of demand from customers	10	Risks too high	1
The company feels that it does not need it	9	Other	1
Lack of financial resources	6		

choice. Table 4 ranks the factors most frequently mentioned by these companies. Thus, the lack of experience in this field (16%), time constraints (14%), the absence of clear benefits (12%) and an unfavorable contractual context to the implementation of innovations (11%) were among the most important factors. The factor "The company doesn't know how to do it" is related to the factor "Lack of experience", which reinforces the need for innovation support. Interestingly, the lack of financial resources and the regulatory context are not determining factors, even if they are to be considered in the innovation process. Another element to note is the influence of the contractual context, which is recognized as an obstacle to innovation in the construction industry.

For the respondents having implemented innovation (68% of the total sample), the authors tried to understand the enablers of their innovation process. Table 5 summarizes the highlights participation in training and conferences (16%), the use of consultants (13%), the integration of innovation into the company's business strategy (11%), the reinvestment of part of the profits in innovation (11%) and the recruitment of competent employees (10%).

As investment in innovation has already proven to have a positive impact in other sectors, this study has tried to identify how the Quebec construction industry fares in this regard. Thus, most respondents invest less than 0.5% of their annual revenue (66%) while 10% of respondents report reinvesting more than 3.0% of their revenue in innovation. By considering the type of company, it was possible to see that a majority of general and specialized contractors invested less than 0.5% of their revenues in innovations. On the other hand, a majority of suppliers and manufacturers invest more than 1% of their revenues in innovation. In addition, a majority of companies generating between C$50–250 million in revenue reinvest between 0.2 and 0.5% in innovation. Those generating between $5 and 25 million annually invest between 0.5 and 1.0% of their revenues. The biggest share of companies that invest more than 3% were companies generating more than $250 million in revenues. Finally, the

Table 5 Enablers of innovation according to the survey (N = 109)

Enablers	Percent (%)	Enablers	Percent (%)
Participation in training courses on innovation	16	No support implemented	4
Consulting	13	Partnerships with colleges or universities	3
Innovation integrated into the business strategy	11	Reward for innovation in the company	3
Reinvestment of part of the profits in innovation	11	Evaluation of the company's implemented innovations	3
Recruitment of employees with skills related to innovation	10	Innovation division/subsidiary	2
Innovation Committee	8	Formalized innovation process (Kaizen)	2
Business plan on innovation	4	Innovation manager appointed on projects	2
Research and development pole (R&D)	4	Other	1
Appointment of an innovation manager	4		

majority of companies counting between 101 and 500 employees, which represent almost a third of the sample, reinvest between 0.2 and 0.5% of their annual revenues in innovation. The highest proportions of very large corporations (more than 500 employees) invest in the 0.2–0.5% range and more than 3%.

Finally, the survey reveals the drivers of technological innovation for the respondents. As shown in Table 6, innovation was implemented mostly at the initiative of management (23%), due to the desire to improve performance on projects (19%) and

Table 6 Drivers of innovation (N = 109)

Drivers	Percent (%)	Drivers	Percent (%)
Management's decision	23	Need for technical elaboration	5
Willingness for Improvement	19	Design trends	3
Competitiveness	16	Environment and Sustainability	3
Innovation strategy	12	Laws and Regulations	2
Proven technology	10	New partnerships	1
Customer's request	5		

to increase the company's competitiveness on the market (16%). What motivated upper management to implement innovation requires more investigation. Surprisingly, the influence of the client as a motivation for innovation is minor, whereas the literature review gave them some importance as a driver of innovation.

4.4 Implemented Innovations and Their Impact

After having investigated the respondents' profiles, their willingness to innovate and the factors influencing the implementation of technological innovations in their company or on their projects, the survey then looked into specific innovations, their characterization and their impact. Each respondent was asked to identify and comment upon up to three specific innovations. A total of 109 instances of technological innovation were identified and analysed through the survey.

The principal expectations around the impact that the innovation, once implemented, would have were around gains in time (13%), productivity (12%), costs (11%) and quality (10%). The respondents were then asked to evaluate if these expectations were met. In this regard, 71% of respondents indicated that the innovation identified met their expectations to a high or very high level. At the same time, 58% of respondents indicated that they were satisfied with the return on investment (ROI) linked to the specific innovation. Conversely, 25% of respondents were still assessing the ROI on these specific innovations. Of these innovations where ROI was still being assessed, 81% had been implemented less than 2 years ago.

As productivity improvement is crucial in construction projects, and at the center of this research project, the respondents were asked to assess the impact of the innovations had on their productivity, on a scale from 1 to 5 (5 being the highest degree of impact). 57% of the technologies identified are perceived as having had a significant or major impact on productivity (4 or 5). On the other hand, 14% of the innovations identified were perceived as having little or no impact (1 or 2).

As a means to validate the respondents' capability to properly evaluate the impact of innovation within their organization, the survey was designed to investigate the means and methods used to track and measure their performance. In this regard, productivity (26%), costs (23%) and schedule (14%) were the 3 indicators that are most used by companies to evaluate the impact of technology implementation on the performance of their projects. Moreover, the means of measuring the impacts of technologies were done mostly through comparison with similar projects (29%), through comparison with project tasks to which the technology is not applied (22%), or through internal surveys (23%). 7% of the innovations identified were not tracked or measured.

5 Discussion and Conclusion

The research presented in this paper aimed to document the state of innovation and its impact on productivity in the Quebec construction sector. Several drivers, enablers, and barriers of innovation were identified and ranked. With regards to drivers, contrary to the literature, the results suggests that clients do not have the biggest influence on innovation. While inexperience in the field and time constraints were identified as major barriers, the lack of financial means was not a predominant one. Interestingly enough, reluctance to invest in innovation was tied to unclear benefits. Enablers such as training, consulting and integration into the company's business strategy are the most common. Once implemented technologies have shown considerably positive results with regards to productivity improvement, project management impacts and ROI. Generally, the results of the survey are encouraging with regards to the strong interest for innovation, and its implementation in the Quebec construction sector. The sample also was largely an innovative one, especially large organizations.

In terms of limitations, the size and revenue of the respondents' companies are not representative of the majority of construction companies in Quebec. Indeed, according to the Commission de la construction du Québec, 81% of Quebec construction companies had fewer than 5 employees in 2019 and the majority of companies operate in the residential sector [6]. The sample therefore does not reflect the reality of the majority of the Quebec construction industry. Even so, the results do provide an understanding of the technological situation of medium and large companies in Quebec. Analyses tend to show a causal link between the large size (financial or salary) of companies and the implementation of innovation. Future investigations on this type of statistics, including correlation analyses, would be relevant to validate the conclusions of this paper. Further research could be expanded to include other disciplines and focus on other sectors to expand the findings to encompass the broader construction industry as a whole.

Acknowledgements This paper is produced bases on a research project in collaboration with the Association de la construction du Québec (ACQ) and the Association des constructeurs de routes et grands travaux du Québec (ACRGTQ). The work presented was partly financed by a grant from the organism Mitacs.

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Evaluating Occupant Feedback on Indoor Environmental Quality in Educational Environments

Y. Abraham and M. Spaan

1 Introduction

Buildings should provide a safe and conducive environment for occupants to carry out their day-to-day activities. Recent changes caused by the pandemic have emphasized the importance of buildings for human health, wellbeing, and productivity. For instance, sustainable and high-performance buildings are designed, constructed, and operated to perform better than conventional buildings while saving energy. Research indicates that the potential for energy savings in commercial buildings is between 5 and 30% [26]. Educational institutions consist of various building types to serve the needs of diverse populations, including instructors, staff, students, and visitors. These buildings have varying daily occupancy and utilization levels which also change throughout the year.

Considering the indoor environmental quality (IEQ), studies have indicated that occupant activities and behavior can impact building energy consumption [12, 26]. The role of occupants in buildings has been studied for a long time, but human behavior is complex and difficult to predict. There are potential energy savings associated with accounting for occupant-related factors in building operations and several opportunities exist to improve building energy efficiency through occupant engagement. Occupant feedback surveys allow for occupant engagement; they can be administered at any point in the building operation to assess the building operation and the modifications that should be made to improve the building conditions. Post occupancy evaluations (POEs) are surveys used to evaluate buildings after being occupied for some time [18]. These evaluations serve multiple purposes, but they are mainly used to determine occupant satisfaction with various parameters related

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S. Walbridge et al. (eds.), *Proceedings of the Canadian Society of Civil Engineering Annual Conference 2021*, Lecture Notes in Civil Engineering 247,
https://doi.org/10.1007/978-981-19-0968-9_4

to IEQ, such as temperature, relative humidity, lighting levels, and air quality [18]. POEs also cover other aspects of the building's function and performance. They identify problems in building operations and pinpoint the factors which could otherwise impact their productivity and health [22]. POEs can also push a building to achieve sustainability goals [20] and is a requirement for building certification with some green building rating systems. Conducting regular building occupant surveys can allow the building owners, operators, or facilities management team to identify problems early and correct them. However, there are limitations to post-occupancy surveys. These surveys could unearth inefficiencies in building operations, leading to higher costs, difficulties in assigning responsibility for the identified issues, and problems with meeting the occupants' expectations [22].

Web-based surveys and applications have been developed to collect occupant feedback in buildings one-time or continuously. In this study, a one-time survey was developed to capture occupant perception, satisfaction, and behavior in relation to IEQ in faculty and staff offices within an educational institution in the US. Building occupants are a good source of information as they provide feedback on how well the indoor environmental conditions meet their comfort needs. This paper's main objectives are to present key findings on the occupants' perception of IEQ parameters, their satisfaction, and behavior related to comfort in their offices. This study identifies the critical areas of concern to occupants and provides preliminary recommendations to improve IEQ in buildings while enhancing building operations.

2 Background

Occupant presence has been identified as one factor that impacts building energy consumption [24]. Other key factors that impact the indoor environment include materials, equipment and processes, heating, cooling, ventilation, and air conditioning (HVAC) processes, and activity [23]. Occupants continuously interact with buildings directly or indirectly and occupant behavior has the potential to increase or decrease building energy consumption. Energy use is also affected by the types of equipment present in the space, the use of the space, and other occupant-related factors. In addition to these, some social factors also affect the occupants and how they interact with space, such as their environmental awareness and concern about energy costs [24].

The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) thermal comfort standards recommend the acceptable comfort level for building occupants and prescribes that at least 80% of building occupants should be satisfied with the indoor environmental conditions in a space [4]. It is therefore critical for the indoor thermal conditions to provide satisfaction to the majority of the occupants. Thermal comfort can be affected by air temperature, humidity, airspeed, radiant temperature, metabolic rate, and clothing insulation [4]. In studies that explored how indoor air quality affects humans, the importance of user engagement in managing indoor environmental conditions was emphasized [23]. In addition to ensuring acceptable thermal conditions and air quality, other parameters, including lighting and noise levels, should also be addressed. For instance, changing the lighting settings impacts occupant behavior, and studies indicate that some individuals perform better in environments with natural lighting [11]. Lighting energy consumption can also be impacted by the occupants' access to the controls. Studies have indicated that providing lighting controls to occupants can lead to energy savings [7, 10]. Information gathering from building occupants is necessary to assess aspects of the building that need to be improved to ensure an acceptable level of occupant satisfaction and prevent adverse health issues and costly utility bills. In educational settings, apart from health, productivity is critical, and the impact of IEQ on occupant productivity has been discussed in different studies.

The main types of occupant behavior observed in buildings include the use of portable devices, changing the number of layers of clothing, adjusting thermostats, and opening and closing windows and doors. Studying occupant behavior is critical considering its impact on building energy consumption [2, 13, 16]. However, there are several obstacles to modeling and quantifying occupant behavior to evaluate its impact on energy consumption [13]. Strategies to reduce the impact of occupant behavior on energy consumption, including modeling and simulation, incentives, and behavioral interventions, have been explored. For instance, occupant-centric HVAC control system modeling would need a lot of occupant and building-related information, such as building envelope information, lighting and plug loads, HVAC system dynamics, and stochastic occupant behavior information such as presence and activities, to more accurately predict occupant needs in buildings. Case studies that explore occupant behavior and satisfaction through real-world scenarios contribute to research on improving building IEQ, occupant comfort, and energy efficiency.

Over the years, a variety of tools have been developed to capture occupant-related information in operational buildings. One of the commonly used approaches to capture this information is through surveys. The Center for the Built Environment (CBE) developed an extensive survey for office building occupants, which has been widely used in different offices [25]. The PROBE survey was developed in the UK in 1995 and is geared toward different building types like offices, educational, and government buildings [17]. Another tool was developed by the National Research Council (NRC) Canada to assess different aspects of office buildings, including an online questionnaire on environmental satisfaction and health [21]. Most of these tools included one-time surveys administered to building occupants focused on their behavior and satisfaction with different building parameters.

3 Methodology

3.1 Research Approach

The study involved a one-off survey of faculty and staff at an educational institution in the US to gather feedback relating to their perception, satisfaction, and behavior in their workspaces. The first step in this research was a review of the literature, followed by the development of the survey, then the distribution of the survey and data collection. Finally, the data were preprocessed and analyzed. These steps are further described in the following sections.

3.2 Survey Questionnaire Development

The initial draft of the survey was developed following a literature review, the author's observation and interaction with occupants, and other survey questionnaires [1, 3, 25]. The survey was modified after a few iterations and feedback from experts, building operators, and peers for the content and readability of the questions. The questionnaire was submitted for approval by the Institutional Review Board (IRB) and pilot-tested with a small group of people to identify any problems with the flow and setup of the questions within the survey development platform (Qualtrics). The final version of the survey was created after several iterations and finally distributed. The steps involved in developing the survey are visually outlined in Fig. 1.

The survey included different question types; the majority were close-ended questions. Participants had the opportunity to provide general comments at the end of the survey in an open-ended question. They also had the ability to enter their preferred response in a text entry box for a selection of the questions. The questions had different rating scales, and a few questions had 7 point scales based on best practices for similar questions in the literature, while some had 5 and 6 point scales. The survey contained 35 questions, excluding the background and demographic questions. This number includes branching questions depending on the answers provided. For instance, when participants responded that they were "moderately dissatisfied," "dissatisfied," and "very dissatisfied," they were led to additional questions asking about the cause of their dissatisfaction with the parameter being assessed.

The survey completion time was noted during pilot testing. The survey was estimated to take about 12 min. After eliminating extreme outliers and non-responses

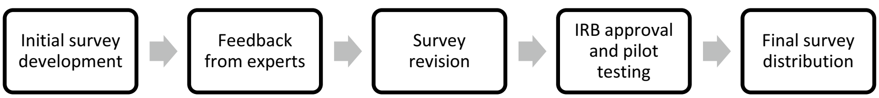

Fig. 1 Survey development process

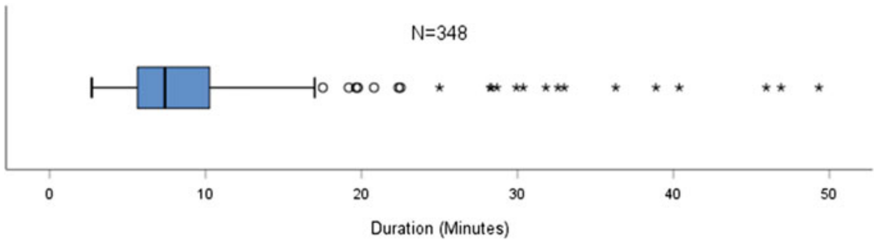

Fig. 2 Boxplot of time taken to complete the survey

at the end of the study, 80% of the data was analyzed, and the median time taken to complete the survey was 7.4 min. The minimum excluding outliers was 2.7 min, and the maximum excluding the outliers was 17.0 min (Fig. 2).

3.3 Participants

The survey was distributed through the institutions' listserve, and participants could voluntarily participate. The response rates were difficult to estimate since the listserve contained most full-time, part-time, adjuncts, and some retired faculty and staff, so not everyone was eligible to participate if they did not have an office on campus. The survey was open for about two weeks during the winter season but had low response rates and had to be shut down prematurely due to the COVID-19 pandemic. Most states went into a lockdown, and people moved to remote work. The breakdown of responses to the demographic data (gender and age) for 357 participants is shown below (Fig. 3).

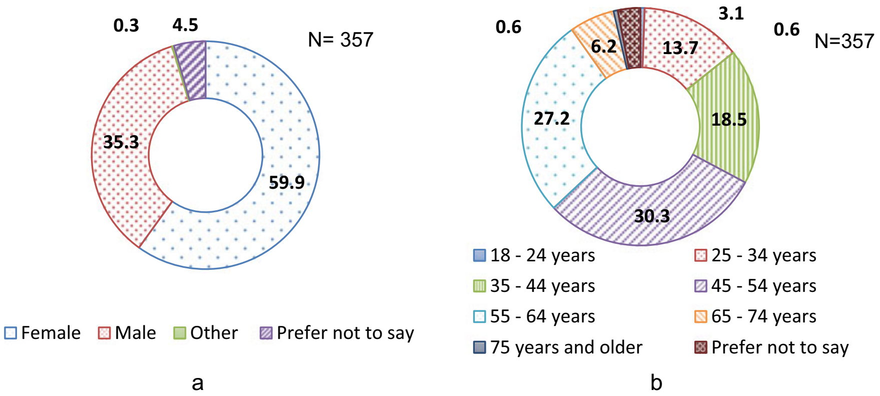

Fig. 3 Breakdown of participants demographic information, **a** Percentage breakdown by gender, **b** Percentage breakdown by age

The responses cover a wide demographic within the educational institution. About 60% of the responses were from females, 35.3% from males, 4.5% did not disclose, and 0.3% selected "other." The most common age group in the survey was 45–54 years, representing 30.3% of the survey respondents, 27.2% were between 55 and 64, 18.5% were between 35 and 44, and 13.7% were between 25 and 34 years.

3.4 Data Analysis

The data was preprocessed and cleaned in Microsoft Excel before exporting it to SPSS version 26, a statistical software, for further analysis. Some responses were eliminated because they were outside the eligibility criteria. For instance, if the respondent did not have an office within the educational institution, they were removed from the study. After eliminating two ineligible responses, it was observed that four hundred and thirty-five (435) individuals had opened the survey sent out to the listserve. The breakdown of responses by percent complete is presented in Table 1—the responses below 100% complete included individuals that did not complete the demographic questions. Three hundred and fifty-eight (358) responses were over 98% complete. Four hundred and seven (407) participants answered at least one question.

The results presented in this paper include occupants' perception of temperature, humidity, airflow, lighting, and noise; occupants' satisfaction with thermal conditions, IAQ, lighting, and noise; preferred indoor temperature, and occupant behavior. Content validity was completed for each of the questions. As earlier mentioned, incomplete responses to the survey questionnaire were not removed, but the variables were analyzed separately for each question. Univariate analysis was used for most of the variables in this paper. The results section indicates the number of items analyzed for each variable considered. The mean satisfaction rating was computed for different parameters within SPSS, and the rankings were presented. Frequency tables were generated in SPSS to understand the number of people that engaged in certain behaviors to improve their comfort. Cross tabulations were computed for the question on the frequency of occupant behavior. The missing data was dropped for item non-response since the non-responses were low [6].

Table 1 Percent completion rates to survey questions

Survey percent complete (%)	Number of participants	Percent of participants (%)
0	28	6.4
1–25	11	2.5
26–50	9	2.1
51–75	1	0.2
76–100	386	88.7

The internal consistency of the data on satisfaction with different parameters was determined using Cronbach's alpha reliability analysis. This analysis checked the extent to which the satisfaction questions in the test measured the same concept. Out of 435 responses, 88.5% were valid, and a Cronbach's Alpha of 0.718 was obtained, which is greater than 0.7 indicating an acceptable internal consistency [5].

4 Results and Discussion

4.1 Reports on Occupants' Perception of IEQ Parameters

This study was completed in the winter season, and the occupants reported on their perception of various IEQ parameters, including temperature, humidity, airflow, lighting, and noise (Fig. 4). From the results, 58% felt their office was cold, cool, or slightly cool; 58.5% felt that the air was too dry, dry, or slightly dry. About 48.6% felt that the airflow was about right, about 50.1% felt that the lighting was neutral, and 48% felt their office was slightly noisy, noisy, or too noisy.

Occupants also reported on their preferred indoor temperature during the winter. ASHRAE recommends indoor temperatures between 20.3 °C (68.5 °F) and 23.9 °C (75 °F) in the winter at 50% relative humidity for building occupants [4]. There were 405 responses to the question on preferred indoor temperature, and 87.1% of the occupants reported their preferred indoor temperature was between 20 °C (68 °F) and 23.9 °C (75 °F) during the winter season. In response to the question about the importance of having control over the thermal conditions in their office, out of 398 responses, 75.6% indicated that they felt it was moderately important, very important, or extremely important. The most common factor contributing to thermal discomfort was that the thermostat is inaccessible or controlled by others reported by 104 respondents. This finding indicates that people are likely to engage in different behavior if the indoor conditions do not meet their requirements. These actions could increase energy consumption, so it might be necessary to consider including some end-user control in buildings [15].

4.2 Report on Occupant Satisfaction

Occupant satisfaction data were collected for thermal comfort, IAQ, lighting, and noise (Fig. 5). The total percentage satisfied (moderately satisfied, satisfied, or very satisfied) with thermal conditions was 51.6%, for IAQ was 58.4%, for lighting was 69.2%, and for noise was 66.6%. Based on ASHRAE's recommendations for thermal comfort, fewer than 80% were satisfied with their offices' thermal conditions. The number of responses for each of these variables is presented in Table 2.

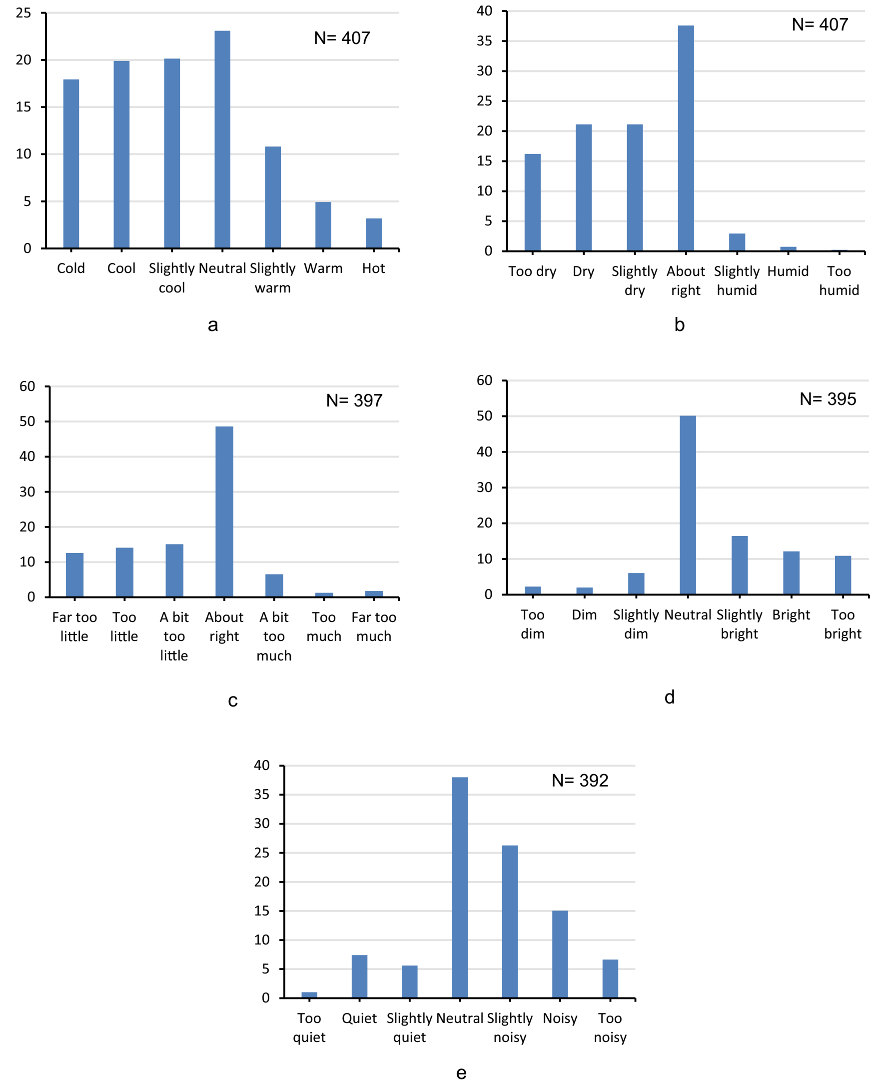

Fig. 4 Occupants' perception of IEQ parameters, **a** Indoor temperature, **b** humidity, **c** airflow, **d** lighting, **e** noise

Occupant satisfaction with the IEQ parameters was assessed on a six-point scale (1—very dissatisfied and 6—very satisfied). The mean satisfaction rating, standard deviation, and ranking for each parameter are presented in Table 2. Based on the ranking, the highest satisfaction was with the lighting, while the least satisfaction was with the thermal conditions. The occupants were also asked about their overall satisfaction with their personal workspace, and the mean satisfaction rating for 386

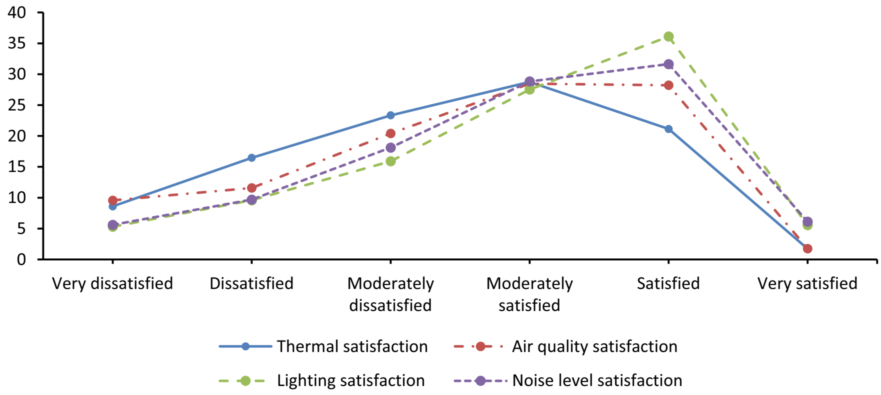

Fig. 5 Reports on occupant satisfaction with different IEQ parameters

Table 2 Mean satisfaction rating of IEQ parameters

IEQ parameters	N	Mean satisfaction	Standard deviation	Rank
Lighting satisfaction	396	3.96	1.27	1
Noise satisfaction	392	3.90	1.28	2
Air quality satisfaction	397	3.59	1.31	3
Thermal satisfaction	407	3.43	1.27	4

valid responses was 3.91. On average, their responses were close to the moderately satisfied rating. Considering these satisfaction ratings, the occupants are likely to engage in different behavior to improve their comfort indoors. Studies have shown that dissatisfaction with thermal comfort, air quality, and noise can trigger behavior that impacts energy consumption.

4.3 Reports on Occupant Behavior

The cross-tabulation (Table 3) shows the occupants' feedback on their behavior in response to different indoor environmental conditions. They were asked about how frequently they engage in the listed behavior. There were 387 responses to the questions on occupant behavior in response to the indoor environmental conditions. The missing data from individual survey items are indicated in the table. The results show that the most common behavior is opening the door to improve their comfort (reported by 47.5% of the respondents). The survey showed that 81.4% do not have access to an operable window. The majority of the occupants reported never using a portable humidifier, portable dehumidifier, portable heater, or fan. However,18.7% of the occupants frequently or always used portable heaters.

Table 3 Occupants' behavior in response to indoor environmental conditions

	Never (%)	Rarely (i.e., once every 3 months) (%)	Occasionally (i.e., twice every month) (%)	Frequently (i.e., twice every week) (%)	Always (i.e., every day) (%)	N/A (%)	Missing (%)
Open and close the windows	14.0	1.3	1.6	1.6	0.3	81.4	0.0
Open and close the window shading device	10.9	15.0	14.5	10.1	9.3	40.3	0.0
Open your office door to improve your comfort	9.8	6.7	10.6	10.3	47.5	14.5	0.5
Regulate the thermostat to make the room warmer or cooler	13.2	10.6	8.5	6.5	5.2	56.1	0.0
Monitor indoor temperature change on a thermostat	17.1	8.0	5.4	7.2	8.3	54.0	0.0
Use a portable fan	33.6	11.1	14.5	14.5	9.0	16.8	0.5
Use a portable heater	48.3	7.8	7.0	10.9	7.8	18.3	0.0
Use a portable humidifier	57.9	2.8	1.8	2.3	4.4	30.7	0.0
Use a portable dehumidifier	65.1	1.3	0.3	0.0	0.3	33.1	0.0
Complain to facility managers the building operator	38.8	39.5	12.7	1.3	0.5	7.2	0.0

In addition, the occupants discussed their actions to improve comfort. The most frequently reported actions were as follows: 123 reported putting on more layers of clothing, 77 indicated that they complained to the facility manager or maintenance team, 72 used a portable heater, and 52 used a portable fan when they were uncomfortable. They engaged in adaptive (i.e., opening and closing windows, adjusting thermostats) and non-adaptive actions (i.e., wearing additional layers of clothing) [14].

4.4 Recommendations for Building Operation

Several benefits can be accrued from addressing occupants' needs by providing better IEQ, as highlighted in other studies. Some of these include improved productivity, reduced building-related illnesses and sick building syndrome, improved wellbeing, reduced energy consumption, improved IAQ, and reduced operations costs [8, 9, 19]. As a result of this study's findings, the following recommendations were provided to improve occupant comfort and satisfaction with IEQ in buildings.

- Occupant feedback surveys should be available for occupants to file their complaints and report on their comfort as needed. Also, they can be conducted on a seasonal or yearly basis to determine if the building meets occupants' IEQ needs. In addition to data from the building management system, facility managers can also diagnose problems routinely from the feedback collected. Intelligent communication systems that allow for two-way interaction between the occupant and building automation systems can reduce complaints and provide information to better predict occupant preferences indoors.
- Training can allow occupants better understand how the building operates. It can also provide awareness of the impact of their behavior and actions on the building. Refresher training can also be incorporated on an ongoing basis to remind the building end-users of the building operation.
- Providing some level of control to building occupants after the training period can provide additional benefits as occupants may be more mindful and indicate their preferences for better prediction of critical IEQ parameters.

5 Conclusions

In conclusion, this study emphasizes the importance of occupant feedback surveys during a building operations phase. The information collected through the surveys provides insight into occupant's perception and its impact on end-users. The main findings highlight the need to include building occupants' preferences in the operations phase as this could affect occupant satisfaction resulting in reduced productivity and adverse health impacts. Strategies to improve occupant comfort should be further explored, including considering more end-user controls. One limitation of this study was the inability to accurately determine the survey response rate. There were some incomplete responses, which were not excluded from the analysis. Individual survey items were analyzed for a high-level analysis of the data collected. Also, additional responses could not be collected due to the lockdown and switch to remote work. Future work will include further analysis of the data, including multivariate analysis and correlations, to determine the relationships between different variables, such as gender differences, age, and the number of hours spent in the office.

Acknowledgements The authors would like to thank the Rochester Institute of Technology Office of Sponsored Research for the seed funding that supported this work. The authors would also like to thank the study participants and individuals that provided feedback on the survey questionnaire.

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Teaching Construction Project Planning and Control Using a Management Game Approach

E. Pereira and N. Thom

1 Introduction

The complex characteristics of construction projects result from dynamic conditions, uncertainties, and a fragmented industry. These unique characteristics make it challenging to deliver projects within quality, safety, cost, and schedule goals. To accomplish projects successfully, construction managers should have a high level of technical and soft skills to analyze and make proper decisions on using resources efficiently and keeping the project on track.

Academic programs are continuously under pressure to close the gap between academic and industry skills [5]. One approach to bridging this gap is by embedding Construction Management (CM) courses within Civil Engineering courses. This provides graduates with the necessary critical thinking skills needed for successful project management. Although the traditional lecture-based instructional methods can provide students with enough context to develop problem-solving skills, they lack the dynamic environment that accompanies a real-world construction project. [14], suggested that topics in the CM domain are introduced one at a time, with students moving to the next topic only after being evaluated on the previous. In contrast, problem-based learning (PBL) exercises provide context and motivation for learning while using a collaborative environment for decision-making [11]. According to [8], PBL can assist students in developing (1) critical thinking, (2) decision-making capability, and (3) transferable skills.

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S. Walbridge et al. (eds.), *Proceedings of the Canadian Society of Civil Engineering Annual Conference 2021*, Lecture Notes in Civil Engineering 247,
https://doi.org/10.1007/978-981-19-0968-9_5

The CM game approach has been widely suggested as an effective tool in teaching management and engineering skills and as part of a PBL exercise [2, 4, 15]. Through the use of games in teaching and training engineering, it is possible to replicate different phases of a project such as construction contracting or bidding [1, 3, 9, 10], project planning and control [6–8], and project maintenance [13]. Games allow students to be actively involved in education and enable instructors to develop active learning in a student-centred learning environment [12]. The benefits of game-based learning are that students use a combination of knowledge to choose from the many given solutions to make a decision. It helps link theory and real-world problems to enhance the students' understanding of the subject [10].

This manuscript describes a game-based approach to teach undergraduate civil engineering students project planning and control. The game context is to plan and virtually build a heavy-construction project in Nottingham—United Kingdom. During the game, the students are exposed to concepts in a range of areas such as: highways, reinforced concrete structures, and drainage systems, as well as situations that help develop their communication and critical thinking skills. Ultimately, with the game-based approach, the students are better prepared for the industry.

2 Objectives of the Game Approach

The game approach described in this paper is designed to teach first-year undergraduate students about the processes, planning, and control of construction projects. As this will be the first time students experience working with technical information and construction projects, the game objectives are developed for the appropriate level of student knowledge. Also, inasmuch as possible, the game replicates the real behaviour of construction projects. There were several detailed objectives to be considered in the design of the game:

- Construction sequencing: The game should replicate the correct sequencing of construction tasks. All the project tasks relationships are Start-to-Start or Start-to-Finish, and students must identify these relationships.
- Realistic: The game approach should replicate some aspects of a real construction project. Therefore, the students' decisions should impact project construction progress and financial terms.
- Uncertainties: The game should account for risks that will affect the project's performance, while still making it possible to complete and make a profit.
- Resources: Based on the project's technical information, students should determine the resources required for completion. Technical drawings and information should be presented in a manner that 1^{st-}year students can understand.

3 Project Description and Preliminary Activities

One of the critical aspects of a game approach is to decide what type of project to use. The project should be complex enough to provide a realistic challenge and simple enough to be contained in a game [2]. A complex project would create difficulties for first-year students and potentially demotivate their participation and engagement. The game approach described herein uses a road project with a simple bridge structure to introduce students to the basic concepts of highway construction and reinforced concrete structures.

The fictitious project is located close to the city of Nottingham—UK. The project involves building a 4 km highway and three reinforced concrete structures (Fig. 1): Railway Bridge, Shelford Road Bridge, and Trent River Bridge. The structure of the bridges is simplified for the sake of the exercise. The project also contains drainage on both sides of the road, eight 1000 mm cross drains beneath the carriageway, and four relief culverts to allow floodwater to flow under the road. The project is broken down into more than 750 tasks, 33 types of material, 33 construction processes, five types of labour, and 23 items of plant.

Before simulating the project construction, students are asked to detail a work breakdown structure (WBS) and identify the critical tasks. Using the material provided by the instructors, they are also required to develop a preliminary project schedule using Microsoft Project. The project is divided into five 12-week periods and is expected to be completed by week 60 (300 working days).

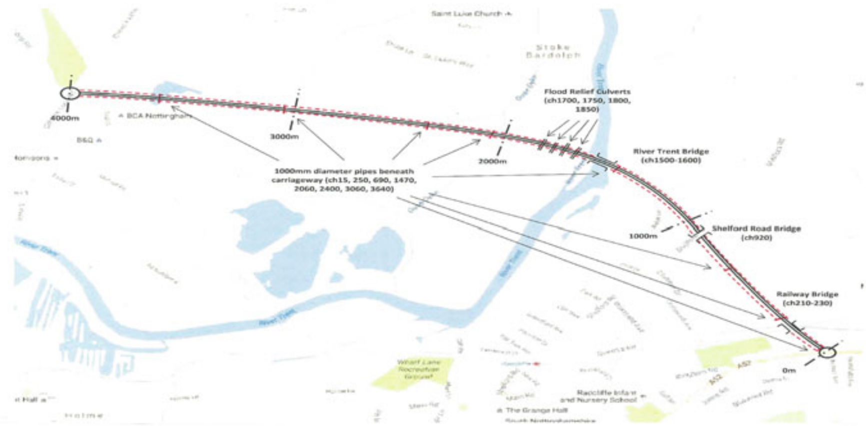

Fig. 1 Project overview

3.1 Material Provided to the Students and Games Rules

Students are provided with the following information to develop the preliminary schedule:

- Longitudinal Profile: It provides information on the current terrain and finished road elevations. This information is critical to estimate the amount of cut/fill in the project.
- Highway and Drainage System Technical Drawing: It provides a cross-sectional overview showing the thickness of each road layer, edge slope, and road width (Fig. 2). The file also presents culvert information (section, reinforcement and edge slope), drainage location, and bridge pavement layers.
- Bridge Drawings: Each bridge has its own technical drawing. Each drawing shows the foundation type, quantity of reinforcement, cross-sections, longitudinal beam specifications, abutments, and wing walls. In addition, a BIM model of the Trent River Bridge (Fig. 3) is provided to facilitate the understanding of the bridge elements. Students can interact with this model and check the element properties such as material type, area, volume, size, etc.
- Costs, Rates, and Productivities: It provides a standard rate for materials, equipment and labour, and costs for materials/processes undertaken by subcontractors (e.g., erecting the site compound). It also states limiting amounts of material and equipment that can be ordered within a ten working day period, (examples in Fig. 4a), and the productivity and resource requirement for each task (equipment and labour) (examples in Fig. 4b).

The game approach contains some rules to assess each student groups' performance and to simplify comparisons between the groups.

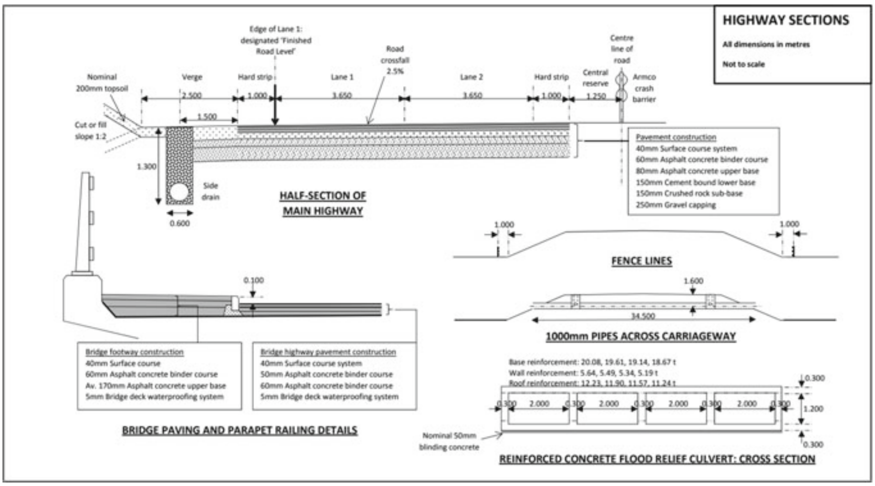

Fig. 2 Highway cross section, drainage system, culverts, and bridge pavement cross section

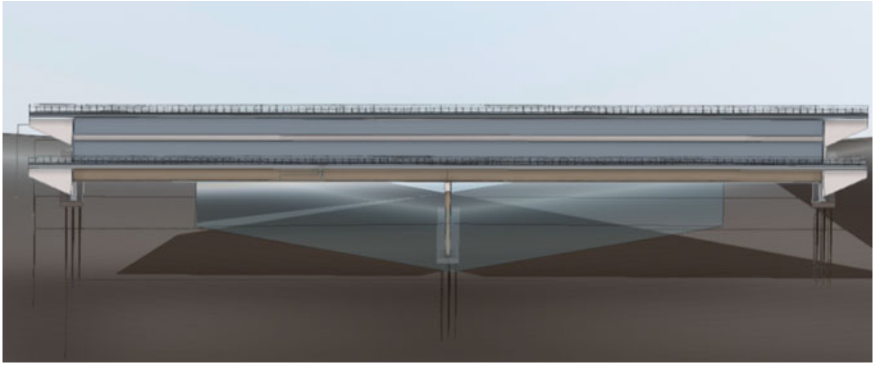

Fig. 3 Trent river bridge BIM

1	Direct Cost Schedule (excluding overheads)				Limit for	
2	Resources:	Normal Rate (£)	Unit		normal rate	
3	Site compound	125000	Item	includes construction	no limit	
4	Temporary railway crossing	200000	Item	includes installation	no limit	
5	Railway Bridge (subcontractor)		Item	includes construction	no limit	
6	Fencing posts and bars	14.8	m	(and removal)	no limit	
7	Suitable fill (imported)	5.1	cu m		6000	in 2 weeks
8	Capping	7.6	cu m		3000	in 2 weeks
9	Sub-base	11.2	cu m		3000	in 2 weeks
10	Cement bound lower base	43	cu m		2000	in 2 weeks
11	Asphalt upper base	77	cu m		1500	in 2 weeks
12	Asphalt binder course	80	cu m		1200	in 2 weeks
13	Asphalt surface course	89	cu m		800	in 2 weeks
14	Porous drainage pipe 300mm	9.5	m		no limit	

a

Productivity (10 hour working day)			
Fencing	400	m / day	1 backhoe, 0.5 flatbed, 0.1 forklift, 0.5 van, 1 auger, 0.5 engineer, 0.5 foreman, 2 labourers
Topsoil strip [assume 200mm thick]	340	m3 / day	1 excavator, 1 dumper, 0.5 van, 0.5 engineer, 0.5 foreman
Cut [dumpers if river crossing available]	840	m3 / day	1 excavator, either 2 dumpers or 7 tipper lorries, 0.5 van, 1 engineer, 0.5 foreman, 1 labourer
Fill	840	m3 / day	1 dozer, 1 roller, 0.5 van, 1 engineer, 0.5 foreman, 1 labourer
Capping	560	m3 / day	1 dozer, 1 grader, 1 roller, 0.3 van, 0.5 engineer, 0.5 labourer
Sub-base	420	m3 / day	1 dozer, 1 grader, 1 roller, 0.3 van, 0.5 engineer, 0.5 labourer
Lower base (CBGM)	400	m3 / day	1 roller, 1 paver, 0.5 van, 1 engineer, 0.5 foreman, 1 labourer
Upper base (Asphalt)	175	m3 / day	1 roller, 1 paver, 1 sprayer, 0.5 van, 1 engineer, 0.5 foreman, 1 labourer
Binder course	140	m3 / day	1 roller, 1 paver, 1 sprayer, 0.5 van, 1 engineer, 0.5 foreman, 1 labourer
Surface course	85	m3 / day	1 roller, 1 paver, 1 sprayer, 0.5 van, 1.5 engineer, 0.5 foreman, 1 labourer
Side drains [excavate, lay pipe, fill]	70	m / day	1 backhoe, 0.5 flatbed, 0.5 van, 0.5 engineer, 1 foreman, 4 labourers
Cross drains [excavate, lay pipe, fill]	15	m / day	1 backhoe, 0.5 flatbed, 0.5 van, 0.5 engineer, 1 foreman, 4 labourers
Topsoiling	280	m3 / day	0.5 excavator, 1 dumper, 1 dozer, 0.3 van, 0.3 engineer, 0.5 foreman
Crash barrier	100	m / day	1 backhoe, 0.5 flatbed, 0.1 forklift, 1 van, 1 auger, 0.5 engineer, 1 foreman, 4 labourers

b

Fig. 4 Rates for equipment and limit for normal rates (**a**), productivities and resources required for tasks (**b**)

For the first 12-week period, student groups are required to submit a document defining the tasks they choose to carry out, the required equipment (number of days), quantity of material, and site personnel. If tasks are not completed within the allotted time, the groups need to adjust and then submit the working plan for the next 12-week period. This iteration continues for the entire 60 weeks.

Each of the 750 predefined tasks has a nominal duration of two weeks, and students should manage the number of resources so each task can be completed. There is also a limit on the number of pieces of equipment or quantity of material used in two weeks (the costs increase by 50% if the normal rate limit is exceeded). The number of resources utilized is automatically assessed by the game controller based on the number of days required by each equipment or site personal. For example, if a backhoe is required for 11 days in two weeks (10 working days), the system would assign two pieces of equipment. Costs for personnel, materials, and equipment double if not planned/ordered in advance. If a task is not completed within the assigned time period, this delays the start of all successive tasks. For example, if task 1 was not completed within period 1, it will be automatically put off to period 2 and delay the start of task 2 to period 3. Payments are made for every 25% completion increments, and there is a 2% interest charge on any bank deficit at the end of each 12-week period.

An example to demonstrate the number of resources required to complete a task is presented below. To complete the project fencing (7800 m) in 10 working days, assuming a productivity rate of 400 m/day (Fig. 4b), the quantity and number of equipment/site personnel required are presented in Table 1.

Twelve common risks that can impact the performance of a construction project are included in the gameplay (Fig. 5). These risks are presented on a card, one of which is drawn per submission. These risks can impact equipment/labour productivity, increase project costs, or shut down the site.

Table 1 Resources required to complete 7800 m of fencing

Category	Resource type	Daily requirement to complete 400 m	Total quantity	Unit	Number of equipment/site personal[a]
Material	Fencing posts and bar	400	7800	m	–
equipment	Backhoe	1	20	Days	2
	Flatbed	0.5	10	Days	1
	Forklift	0.1	2	Days	1
	Auger	1	20	Days	2
Site personal	Engineer	0.5	10	Days	1
	Foreman	0.5	10	Days	1
	Labourer	2	39	Days	4

[a]Number automatically assessed by the game controller based on the number of days required in a 10 working days period

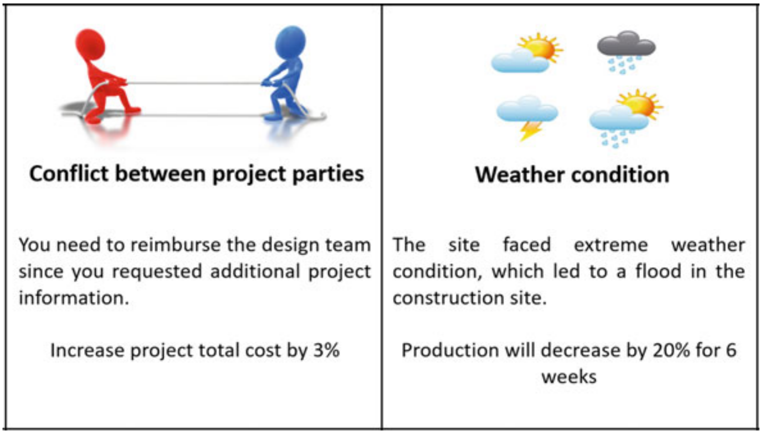

Fig. 5 Examples of project risks

4 Gameplay and Control

Each group should submit an Excel file with all the tasks to be performed in a 12-week period and the required materials, equipment, and site personnel (Fig. 6). The game controller is implemented using a Macro, which automatically accesses the data submitted by each group. Once the information is uploaded, the game controller checks the tasks that can be completed (respecting task-precursor relationships), calculates the project's costs, the project completion level, and defines the payment each group will receive. As a note, project costs are incurred based on the resources required, cost of stockpiled material, and interest rates. Payment is based on completing every 25% percentile of each main project task/activity (e.g., Earthmoving, Bridge, Drainage system, etc.)

The game controller also updates the groups' submission files with the project performance results. The updates contain a list of the materials, equipment, and personnel that were under-ordered/unused and the degree to which the tasks were completed (100% or 0). It also shows the expenditure for each 2-week period, cost of

Materials	Unit	Quantity
Fencing posts and bars	m	8000
Suitable fill	cu m	
Capping	cu m	6000
Sub-base	cu m	1500
Cement bound lower base	cu m	1500
Asphalt upper base	cu m	1500
Asphalt binder course	cu m	2400
Asphalt surface course	cu m	2400
Porous drainage pipe 300mm	m	
Concrete drainage pipe 1000mm	m	
Pea gravel	cu m	
Crash barrier + posts	m	

Equipment	No of days
Excavator + operator	101
Backhoe loader + operator	38
Off-road dump truck + driver	71
Dozer + operator	8
Motor grader + operator	8
Vibrating roller + driver	9
Large crane + operator	
Small crane + operator	12
Pile driver + operator	17
Paver + crew	2
Bitumen sprayer + driver	2
Flatbed truck	35

Roadworks		Topsoil	Cut					
Start(m)	Finish(m)	Strip	0-1m	1-2m	2-3m	3-4m	4-5m	5-6m
0	100	4	4					
100	200	4	4					
200	300	4	4					
300	400	4	4					
400	500	4	4					
500	600	4	4	4				
600	700	4	4	4	4			
700	800	4	5	5	5	5	5	
800	900	4	5	5	5	5	5	5
900	1000	4	6	6	6	6	6	6
1000	1100	5	6					

Fig. 6 Element of a student submission folder

Materials	Unit	Under-ordered	stockpiled Unused
Fencing posts and bars	m		400
Suitable fill	cu m		41836.3
Capping	cu m		2508
Sub-base	cu m		1346
Cement bound lower base	cu m		1500
Asphalt upper base	cu m		1500
Asphalt binder course	cu m		2340
Asphalt surface course	cu m		2370.4
Porous drainage pipe 300mm	m		
Concrete drainage pipe 1000mm	m		
Pea gravel	cu m		
Crash barrier + posts	m		

Equipment (machine days)	Under-ordered	Unused
Excavator + operator	9.80082	
Backhoe loader + operator		0.995
Off-road dump truck + driver		9.823
Dozer + operator		1.398
Motor grader + operator		1.398
Vibrating roller + driver		1.621
Large crane + operator		
Small crane + operator		9.21
Pile driver + operator		0.513
Paver + crew		1.223
Bitumen sprayer + driver		1.223
Flatbed truck		4.807

Percentage Complete Roadworks		Topsoil	Cut					
Start(m)	Finish(m)	strip	0-1m	1-2m	2-3m	3-4m	4-5m	5-6m
0	100	100	100					
100	200	100	100					
200	300	100	100					
300	400	100	100					
400	500	100	100					
500	600	100	100	100				
600	700	100	100	100	100			
700	800	100	100	100	100	100	100	
800	900	100	100	100	100	100	100	100
900	1000	100	0	0	0	0	0	0
1000	1100	100	100	0	0	0	0	0

(a)

Expenditure:	1st 2 weeks	£ 375000
	2nd 2 weeks	£ 250903
	3rd 2 weeks	£ 118605
	4th 2 weeks	£ 1129396
	5th 2 weeks	£ 1092826
	6th 2 weeks	£ 964425
	Surplus materials (stockpiled)	£ 1231.2
	Vastagent, labour & materials)	£ 3001
	Interest charges	£ 20275
	TOTAL	£ 3955662
Payment this quarter:		£ 3091896
Current bank balance:		£ -863766

(b)

Fig. 7 Output provided by the administrator to each group (**a**), breakdown of each 2-week expenditure (**b**)

stockpiled material, wastage cost, interest charges, payment, % completed for each major part of the project, % overall project completion, and the current bank balance (Fig. 7). The groups can also compare their cost and schedule performance with other groups in the overall performance graphs (Fig. 8).

By comparing the game controller results to their preliminary schedule of project performance, students can determine if they are ahead/behind schedule or under/over budget. The students should use the preliminary schedule to define the tasks that need to be completed in the next 12-week period and can request the required amount of material, workers, and equipment from the game controller. In total, there are five submissions per group (Preliminary schedule, WBS, and weeks 1–12; weeks 13–24; weeks 25–36, weeks 37–48 and weeks 49–60). The winning group is determined by the degree of project completion and the amount of profit obtained.

Based on student feedback, the game approach has helped them understand construction processes, how their decisions and risks affect project performance, the relationships between tasks, project planning, and control tasks. Furthermore, the competition aspect of this activity kept them engaged in the coursework, enhanced creativity and strengthened group communication processes.

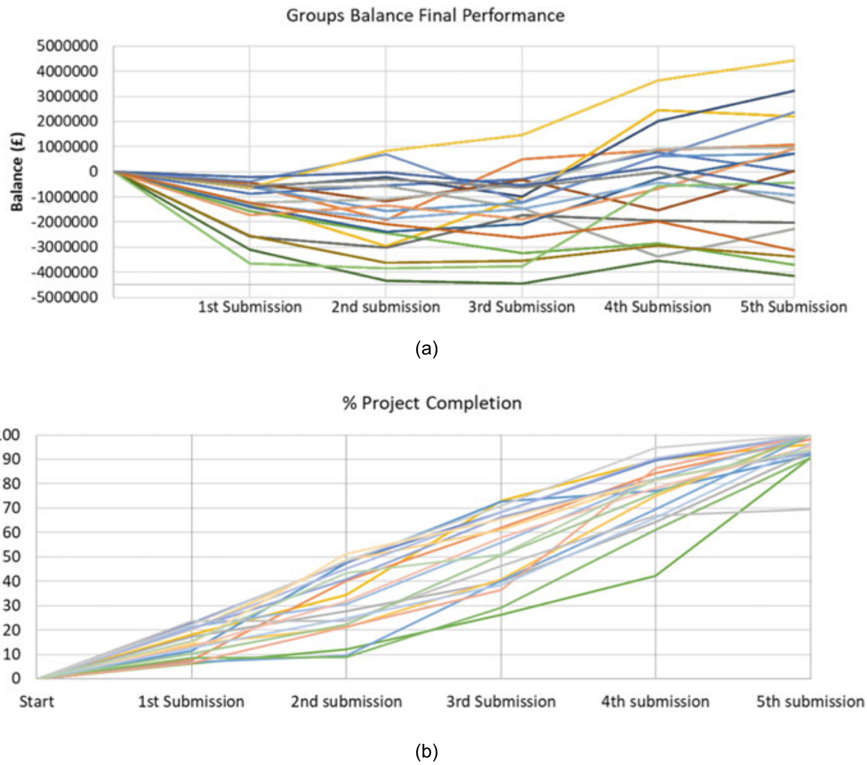

Fig. 8 Overall performance graphs **a** Balance, and **b** project % completion

4.1 Future Challenges and Planned Enhancements

Some aspects of the game can be improved to enhance the player/student's experience. The first aspect is to develop a Graphical User Interface (GUI), so students can enter their information in a user-friendly environment and receive more sophisticated feedback (with additional graphs showing the current progress compared with the current game set-up). The second aspect is to develop a BIM model for the entire project. By linking the BIM model to a Virtual Reality plug-in on Revit (such as Enscape), the students can have a VR experience of construction engineering and project scheduling. Lastly, the BIM model can be further linked to game engines such as Unity. The integration will allow the development of 4D videos and make it easier for students to understand task sequencing.

5 Conclusion

Planning and control of construction projects is a challenge in practice. This paper describes a PBL game approach used in teaching undergraduate civil engineering students Construction Management concepts. The scope of the project was to enhance students' understanding of a variety of construction disciplines (such as reinforced concrete, highways, and drainage) and, to some extent, replicate the risks that may affect the project performance. The game also reinforced the importance of group work and developed students' decision-making skills.

It should be noted that the game approach described here is a work-in-progress, and new versions will be developed based on student suggestions and lessons learned. Some gaps identified in the proposed game approach are related to (1) submission process (the game controller will not produce results if the student enter the wrong data type), (2) previous knowledge on construction processes is needed (presentations during the activity may assist students in understanding aspects of heavy construction projects), and (3) mobilization time and cost is not considered. However, the initial feedback from students indicates that this activity has a great potential to develop project planning and control skills.

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Integrating Building Information Modeling (BIM) and Sustainability Indicators and Criteria to Select Associated Construction Method at the Conceptual Design Stage of Buildings

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1 Introduction

The AEC industry needs a focused, sustainable approach to determine and establish design and construction strategies to improve the sustainability of buildings at the conceptual design. Sustainable design is seen as one of sustainability's main concepts required to attain sustainable buildings whose objectives are to improve the efficiency in using natural resources throughout their life cycle; and to create facilities that are livable, comfortable, and safe while minimizing their impacts on society, the environment, and the economy. The environmental part of sustainability criteria includes sustainable sites, water efficiency, energy and atmosphere and materials and resources; while the economic part focuses on the efficient use of resources and on lowering the lifecycle cost, whereas the sociocultural criteria cover the indoor environmental quality and innovation and the design process [1]. Sustainability assessment method uses tools, models, and frameworks to perform calculations, analysis, and simulations within the sustainable design criteria, which are applied to the building's construction to make decisions related to selecting suitable alternatives. Thus, to evaluate the sustainability performance of a building, a rating system (i.e., LEED) is used to draw its economic and social advantages while helping the surrounding community, both socially and environmentally [2]. Sustainable construction involves the use of building methods to enhance sustainability efforts. Traditional construction has been indicated to be wasteful [3], resulting in a huge impact on the environment because different construction methods would lead

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S. Walbridge et al. (eds.), *Proceedings of the Canadian Society of Civil Engineering Annual Conference 2021*, Lecture Notes in Civil Engineering 247,
https://doi.org/10.1007/978-981-19-0968-9_6

to different sustainable outcomes [4]. Conventional on-site construction, modular prefabrication and 3D printing-based construction are currently the three essential methods used in building construction.

Building Information Modeling (BIM) is a concept that is used to create and monitor project's digital information throughout its life it integrates numerous sustainable design criteria, which contribute to the social, environmental, and economic agenda of sustainability [5]. It allows for multi-disciplinary information to be superimposed into one model, which creates an opportunity for sustainability measures and analysis to be integrated with the design process [6]. Modular off-site prefabrication and BIM implementation have been identified as the two main areas that have high opportunities to drive efficiency and improvement for the construction industry [7]. Also, BIM is proven to be an effective method to facilitate the implementation of 3D printing in the construction industry; the method of construction can be used in both small and large scale buildings, respectively [8]. Thus, modular prefabrication and 3D printing-based construction offer the potential to improve the unproductive and fragmented practice that is currently used in the built environment. Therefore, this paper proposes a methodology to integrate BIM with sustainability indicators and criteria to identify suitable construction methods at the conceptual design stage of buildings.

2 Literature Review

Sustainability in building construction directs to the connection between environment, economics and social impacts [9]. The pursuit of sustainability and sustainable design remains the mainstream objective of the building design [10]. In order to achieve that objective, sustainability must be understood as a specific form of problem framing that emphasizes the interconnectedness of different sub-problems and scales, as well as the indirect effects and actions that result from it [11]. Therefore, the sustainability goals can be reached by increasing the efficient use of energy, water and materials by buildings while reducing their impacts on human health and the environment over their lifecycle [12]. Sustainable design represents a holistic, integrated, and multidisciplinary approach in which every decision is evaluated against multiple criteria to find the best solution. It integrates cost, duration, operations, maintenance, workmanship, and employee considerations through the following five general parts: (1) optimize site potential; (2) energy efficiency and renewable energy; (3) conservation of materials and resources; (4) water quality, conservation, and efficiency; and (5) enhance indoor environmental quality [9].

Furthermore, sustainable construction materials are the foundation of a sustainable building, they play important roles in building sustainable development as all construction materials impact the environment during their entire lifecycles [13]. Khaled et al. [14] stressed that the selection of sustainable materials is the first step in developing sustainable buildings. Karolides [15], listed six important elements to describe green construction materials, which are: (1) materials that are healthy for the interior environment, (2) materials that are healthy for the outdoor environment; (3) materials that help minimize building energy; (4) materials that do not often need replacement, which are durable, reusable, recyclable, and biodegradable; (5) materials with low-embodied energy; and (6) materials that can be locally obtained. The National Building Science characterized green products as the ones that contain recycled materials, that can save water and energy, and that can decrease the amount of toxic materials consumed. Hence, a simple definition is that green construction materials are environmentally responsible because their impacts are considered over their whole lifecycle.

Generally, a conventional construction method for buildings is plagued with delays, material wastage and cost overruns as the degree of overlap amongst activities is associated with condensed time, which leads to increased project complexity [3]. Modular construction has been recognized as one of the primary construction methods for sustainable off-site construction in the recent past [16]. Off-site prefabrication has significant potential to improve productivity and performance of the construction industry whilst 3D printing stands as the future of construction due to the increased demands for more sustainable, resource-efficient practices and trends for innovative designs and structures. Therefore, the use of any of those construction methods would have different impacts on the required resources, costs and the completion time of construction for buildings, thereby influencing the sustainability of construction [4]. However, selecting a sustainable construction method among different options is still subjective; hence, it is imperative to evaluate the sustainability life cycle of the different construction methods [16] in order to select the efficient and reliable one.

BIM has positively impacted the way the construction industry is building and managing urban spaces as it contains sufficient information about building performance analysis, evaluation and it naturally captures data to support sustainable design [17]. BIM tools can be leveraged to develop virtual intelligent models that are capable to be integrated with other construction management tools (i.e. scheduling and cost estimating) at the early design stage of building to promote collaboration, visualization and constructability reviews to benefit all stakeholders throughout the facilities' lifecycle [18]. According to [19], the technical capabilities of BIM that start with visualization and coordination of architectural design and construction work are complemented with numerous tools that are used at all stages of the construction lifecycle. Ranging from clash detection, requirement management, calculation of energy consumption, comfort simulation, environmental analysis, lighting simulation, facility and space management, lifecycle cost evaluation of design and building components. Evolution in BIM practice is a continuous technological advancement where 6D BIM is one of the essential aspects of creating a flawless innovative building construction. Yung and Wang [20] developed a 6D CAD model, which automatically performs life cycle assessment (LCA) for sustainable buildings as a design aid rather than a post-construction evaluation tool that is motivated by the inability of existing building assessment tools to provide quick and reliable decision support for designs. Jalaei and Jrade [21] developed an automated BIM model that links BIM, LCA, energy analysis, and lighting simulation tools with green building certification system (LEED), which included newly created plug-ins in BIM tool (i.e., Revit) that are capable of measuring the environmental impacts (EI) and embodied energy of building components at the conceptual design stage.

The recent development of Construction 4.0 framework, which is at the centre of the current state of practice by emerging trends and technologies; people and process issues that surround the AEC industry's transformation; BIM; lean principles; digital technologies; and offsite construction, is at the edge of this extensive transformation [22]. Presently, there are strong recommendations for the uptake of modular construction and BIM in order to improve the sustainability performance of the construction industry, their benefits have been well-explored in several studies such as [7, 16, 23]. BIM-based 3D printing can be a new method to adopt by the construction industry in the near future as it can bring obvious benefits and substantial savings in cost and time [24]. It also has the potential to be an effective construction method to facilitate the implementation of sustainable buildings at both small and large scales [8].

Therefore, this study proposes a methodology for the integration of BIM with sustainable design to select the suitable type of construction method associated with the selected design at the conceptual stage by considering: (1) users' interactions and input (facilitate design choice from conventional, modular and 3D printing); (2) users' access to accurate and real-time data about green construction materials and associated families for the three construction design methods; and (3) users' evaluate the sustainability of the design by looking at the level of LEED certification based on the accumulated points by using energy analysis, lifecycle assessment, and lifecycle costing analysis.

3 Methodology

The methodology used to develop the proposed model will automate the integration process by using and customizing the APIs of BIM tool's to enable users to connect their sustainable design and select the suitable construction method through five different modules from within BIM tool (Autodesk Revit). The flexibility of the proposed model makes it applicable to any of the three design and construction methods (i.e., conventional, modular, and 3D printing). This will provide owners, designers and general contractors with more options to make their selection to assess different design alternatives at the conceptual stage of the project's life and accordingly identify the suitable construction method. The path to develop the integrated model is implemented through three main phases: (1) Literature review and data collection to ascertain the actual needs, gaps and expectations; (2) Develop a conceptual integration framework: by using gap analysis to identify their efficient solutions; and (3) Develop the intergraded model, which holds the implemented solutions for the identified gaps.

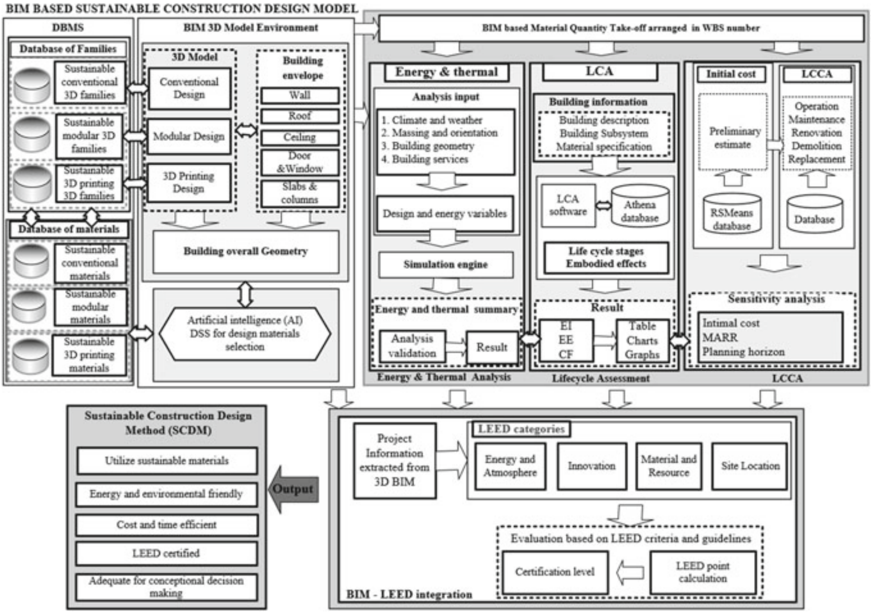

Fig. 1 Proposed model's components

3.1 Model Components and Architecture

The components of the proposed model, which are shown in Fig. 1, consist of the following five modules: (1) A Database Management System (DBMS) module; (2) A Lifecycle Assessment (LCA) module; (3) A Lifecycle Cost Analysis (LCCA) module; (4) An energy analysis module, and (5) A sustainability certification (LEED rating system) module. The five modules are inter-related to each other in a way that makes the proposed model unique, flexible, and yet versatile. The proposed model's architecture, which is illustrated in Fig. 2, consists of four sections: (1) input requirement of data and information; (2) specific criteria required by the different modules to initiate and execute necessary calculations and analysis; (3) various analysis performed by each module directly or via inherited plug-in within BIM environment; 4) the output include analysis and evaluation reports, cost estimating report to support decision-makers at the conceptual design. The proposed model's data flow is illustrated in Fig. 3.

3.2 Proposed Model's Development

Since the proposed model consists of five modules, its development is implemented chronologically in phases as follows:

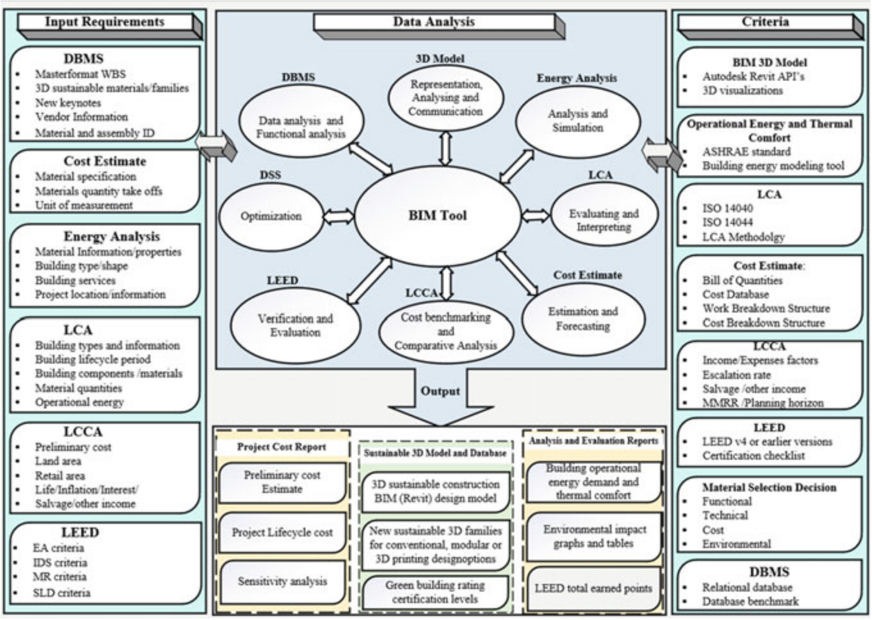

Fig. 2 Proposed model's architecture

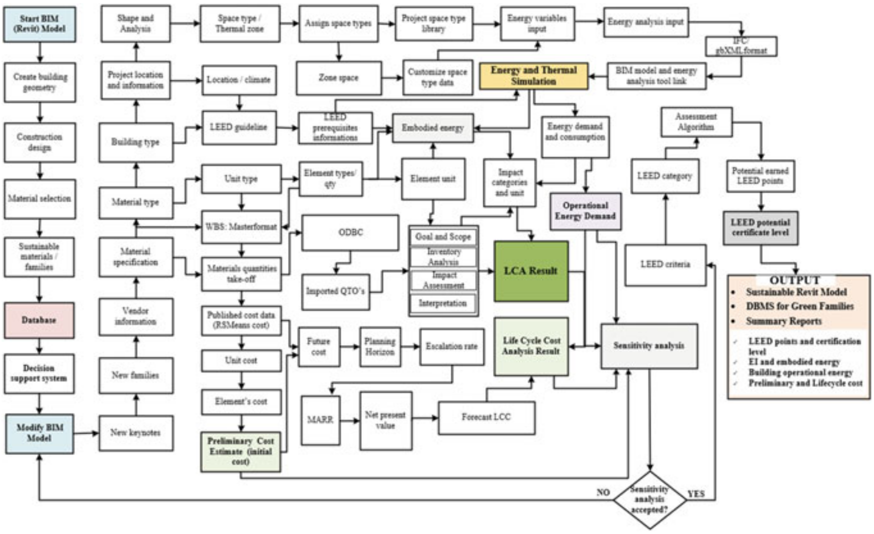

Fig. 3 Proposed model's dataflow

3.2.1 Database Module

The development process of this module follows the size and structural requirements of a relational database which is designed and implemented through two steps: (i) conceptual modelling, and (ii) physical implementation. The main objective of the relational database module is to support the sustainable design of buildings at the conceptual stage therefore, its conceptual modelling starts with requirements analysis where problem investigation and user requirements are identified from the literature review. Conceptual modelling aims at establishing entities and their associated attributes, then their relationships based on all the previously identified requirements. Once the conceptual schema (entities relationship) is derived, the physical implementation starts. BIM-based database management system (DBMS) is physically designed and implemented to systematically compile, organize, store, and provide data for the sustainable design of a building at the conceptual stage.

3.2.2 BIM 3D Design Module

The purpose of this module is to incorporate three different types of conceptual design (conventional, modular and 3D printing) for sustainable buildings by creating a 3D BIM model for each of them, which incorporates 3D families within BIM tool that are created with sustainable construction materials in accordance with the sustainable design requirements. Autodesk Revit is selected as BIM tool to create the 3D building model because Revit is well established and widely used by the AEC industry. The 3D design module is created using sustainable construction families that are stored in the external database of the module, and by collecting plans and sections of different types of buildings to develop side views of the 3D design models that are automatically organized by BIM tool, those models can be used for visualization and to perform necessary calculations, analyses and simulation of the sustainable building.

3.2.3 BIM-Based Energy and Thermal Simulation Module

The BIM-based energy and thermal simulation module is developed over three main steps; (1) the BIM 3D model and other parameters will serve as the building geometry and the main input parameter. They consist of construction materials with thermal proprieties, which were collected and stored in the external database.

Other input parameters components and factors that directly influence a building's energy consumption, such as energy systems, weather conditions, internal load, operating strategies, and schedules. (2) The BIM-building energy analysis and data exchange which will solve the incompatibility between the 3D BIM design model and the existing energy simulation application. So often, the model's conversion will result in loss and distortion of information. Therefore, plug-ins will be created to ensure the consistent and accurate transformation of data and resolve any issues that may arise during the file conversion process in order to create an energy analysis model. (3) In the third step, the BIM-energy simulation will use a whole-building energy modelling engine and energy simulation, which is implemented via an object-oriented programming language (i.e., C#). The detailed result is exported and saved in an appropriate file for evaluation and further documentation in line with LEED Canada rating system by following the guidelines for energy modelling compliance in Canada.

3.2.4 BIM-Based Lifecycle Assessment Module

This module focuses on developing an integrated BIM-LCA workflow needed to perform LCA at the conceptual design stage of buildings. The objective is to evaluate the environmental impact of buildings within the BIM environment and generate continuous feedback of LCA results to guide the design team to improve the environmental performance of a building at the early design stage through a Dynamo connection for Autodesk Revit. The materials quantity take-off of the 3D BIM model and LCA building material database is exported to a spreadsheet via a (*.xls) file format and linked with LCA's material ID's to evaluate their environmental impacts and to calculate and visualize LCA results all within the BIM environment. The database is the source where Visual Programming Language (VPL) Dynamo gets the environmental impacts of the building materials to assess the sustainability of a building. In this study, ATHENA® Impact Estimator (IE) is used as the LCA tool because it is the common one used in North America for that purpose and because it allows users to evaluate the whole building and assemblies based on internationally recognized LCA methodology, ISO 14040 which consists of four stages.

3.2.5 BIM-Based Lifecycle Cost Analysis Module

The objective of this module is to integrate BIM with life cycle cost analysis at the conceptual design stage for the three construction methods: conventional, modular and 3D printing based on the corresponding design to evaluate all the relevant costs over the lifetime of a building. The methodology uses the capabilities of BIM tools to perform LCCA early during the design to enhance the decision-making process and achieve a sustainable design that is of high quality and at a lower overall cost. The proposed methodology adopts the LCCA classification of monetary costs such as initial costs, running costs, and salvage value. All expenses incurred at the different time periods during the life cycle of a building are made current by using the net present value method (NPVM).

3.2.6 Building Sustainability Assessment and Certification (LEED) Module

The objective of this module is to provide a framework where the sustainability of the building 3D design model is evaluated based on the LEED certification system and its associated criteria. The methodology automates the sustainability assessment of the proposed building's design by integrating BIM and LEED certification systems by calculating the potential number of credits that a building may earn. The core of this module is primarily laid on a framework that uses the process of LEED certification and BIM functionalities, which will be applied during the project's conceptual design phases for effective and reliable evaluation of the decision related to the sustainable design. LEED v4, which is published by Canada Green Building Council (Ca GBC) is the reference guide for the building design and construction (BD + C) checklist that provides credits solution for each of the seven categories that are adopted in this study: (1) Location and Transportation (LT); (2) Sustainable Sites (SS); (3) Energy and Atmosphere (EA); (4) Materials and Resources (MR); (5) Indoor Environmental Quality (IEQ); (6) Innovation in Design (ID); and (7) Regional Priority (RP), to ensure consistency with the North American AEC industry.

4 Model Testing

The developed model is tested to verify its capability and workability of a design engine named COMOTH, an acronym for conventional, modular, and three-D printing. This paper is limited to the development and testing of the database module, which is described in Sect. 3.2.1 in a BIM environment. A case study of an actual two-floor residential building is designed and tested using the three types of design and by selecting the associated construction method (i.e., conventional, modular, and 3D printing).

The proposed construction site has a total area of 4457 ft^2, and the building's gross area is expected to be 17,533 ft^2 upon completion. The 3D conceptual design models were created in Autodesk Revit 2020 (as a BIM tool) using the sustainable families and materials stored in the associated database, which is developed for that purpose, as shown in Figs. 4a–c. Once a sustainable design is initiated, the designer runs COMOTH (a plug-in) in a Revit project located at the top bar of the Revit architecture, which opens the design engine with a form requesting to select an option related to the number of floors. There are two building design options for this design engine:1-floor to 3-floor building design and 4-floor and above building design. Selecting a 1-floor to 3-floor building design instructs the design engine to open a three-building design forms, which is associated with that selection as shown in Figs. 4a–c. The design parameters for conventional and modular prefabricated building construction methods such as door, window, wall, floor, ceiling, roof and column and slab stored with their associated information (keynotes, assembly code, specification, and description) ready for use, whilst 3D printing design option has

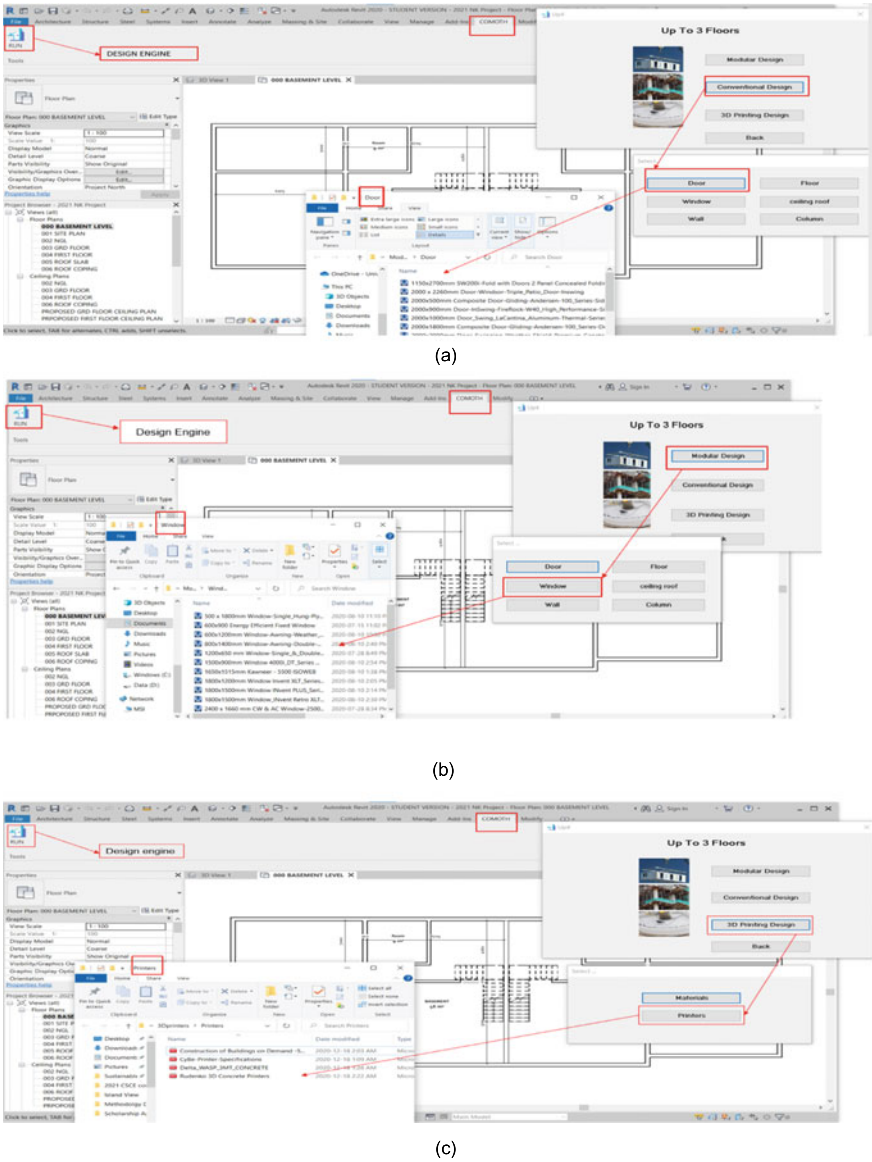

Fig. 4 **a** Conventional design database. **b** Modular design database. **c** 3D printing design database

information about the materials (for wall design) and 3D printers' specifications. Similarly, selecting 4-floor and above building design would instruct the system to open three design options; however, only the conventional and modular designs are compatible with that selection. The 3D printing design option will show a 'not compatible' message as this study is part of an ongoing research project; the developed model is limited to 3D printing design for three floors for now. However, the plug-in is designed to create room for future extension of the 3D printing building design. With all the information for a sustainable design of various building construction methods stored in the COMOTH design engine, the designers can commence and achieve their design in a streamless and cost-effective manner.

5 Conclusion

This paper described the development of a model that integrates BIM tools with sustainability indicators and criteria to help designers select associated and suitable construction methods that best fit the owner's design requirements for sustainable buildings. The focus of this study is on the conceptual design stage where various vital decisions related to proposed projects are made. The novelty highlighted in this paper describes the development of an integrated model that comprises a database management system (DBMS) to aid the design team in selecting the optimum sustainable construction design by using predefined components for proposed projects based on owners' needs and the conceptual design analysis. The developed DBMS is integrated with BIM tool through an automated link by creating new plug-ins (COMOTH) for designers to use when doing the design of proposed sustainable buildings at the conceptual stage in a timely and cost-effective way. However, this is ongoing research, which has the potential for further development, impleentation, and validation.

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Integrating 3D Modeling and GIS-Based Land Use and Multimodal Transport Accessibility Evaluation Model to Design and Retrofit Sustainable Bridges

A. Elgayar and A. Jrade

1 Introduction

Transportation infrastructure is typically considered as a vital pillar for any city, since it supports social development and economic growth. Lately, researchers are focusing their studies on sustainable infrastructure development and transportation planning because current infrastructure is ageing, and the increased population and demand of motorists for mobility and access [1, 2]. Conventionally, transportation planning is based on mobility analysis, which is the main reason for evaluating transportation systems' performance in terms of travel speed and distance. This evaluation approach does not take into consideration broader economic, social and environmental goals. On the other hand, land use planning is evaluated based on geographic and spatial accessibility [2, 3]. A disconnect in the planning approach exists with regards to accessibility, especially since transportation designers are usually not included during the early stages of planning even though transportation and spatial development are interrelated as land use planning can have major impacts on transportation systems [2, 4–6].

Currently, transportation systems planning is shifting towards an accessibility paradigm, which puts individuals at the centre of transportation planning because the use of accessibility as a measurement is the link that can bridge the gap between land use and transportation planning. The concept of accessibility has increasingly become a vital factor that promotes and assists in making sustainable land use and transportation decisions. Thus, accessibility measures provide a holistic approach to sustainable urban development and mobility management. Evaluating transportation

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S. Walbridge et al. (eds.), *Proceedings of the Canadian Society of Civil Engineering Annual Conference 2021*, Lecture Notes in Civil Engineering 247,
https://doi.org/10.1007/978-981-19-0968-9_7

systems based on accessibility can influence the improvement of alternative modes of transportation and provide synergies with land use planning objectives. Additionally, it incorporates evaluation of social, economic, and environmental impacts [2, 4, 7, 8].

Literature indicates that the majority of the existing accessibility evaluation models are Geographic Information System (GIS)-based. This is due to the capabilities of GIS tools to combine, process and analyze large quantities of required spatial data pertaining to multimodal transportation, land use destinations (LUDs), and demographics. Previous developed accessibility evaluation models do not consider all modes of transportation and thus do not capture all impacts of various transportation models on LUDs accessibility [8–10]. Moreover, GIS tools such as ArcGIS by Esri are versatile and offer GIS 3D visualization and analytic capabilities within AutoCAD drawings via a plugin [11]. This makes a GIS-based accessibility module ideal for the evaluation of proposed and retrofitted sustainable bridges using a pre-developed rule-based expert system, 3D CAD modeling, sustainability, and conceptual cost estimation model.

This paper outlines the proposed methodology to derive and inherently embed a Land Use and Multimodal Transportation Accessibility Evaluation (LUMTAE) module in the existing versatile model. Comprehensive literature review was conducted covering the transportation and land use interrelation, existing accessibility evaluation tools, and GIS tools' capabilities and characteristics. The derived GIS-based LUMTAE model will be integrated with the pre-developed 3D CAD sustainable bridge designing model to provide an all-inclusive streamlined designing and planning process.

2 Literature Review

2.1 Transportation and Land Use Systems

The planning and evaluation of transportation networks and land use systems have a history of occurring separately, despite that an interrelationship between transportation and spatial development does exist. Transport planning focuses on improving travel time by increasing speed while land use planning is concerned with the attraction and distribution of population (density). Evidently, there is a disconnect between planning efforts, which can lead to urban sprawl, unsustainable mobility patterns, and low transit ridership levels. However, it is now a fact that travel and land development co-determine each other from numerous studies on their interrelationship. In light of this, it has become apparent that transportation and land use planners need to coordinate efforts for optimal efficiency of network design and land development location decisions [1, 9, 12–14]. A feedback cycle exists between land use and transport with accessibility identified as a common factor. Accessibility directly affects attraction, which, in turn, directly affects location decisions for development and trips. A case study in Washington DC demonstrated that the higher level of accessibility a location may have, the better chance it will have to attract high density development. Thus, establishing that accessibility as a function of transport can shape the land use system and vice versa [6, 14]. The question on how transport and land use systems affect each other via accessibility can be explained as: "the distribution of infrastructure in a transport system creates opportunities for spatial interactions" and it is measured by accessibility, while "the distribution of accessibility in space co-determines location decisions and so results in changes in the land use system" [6].

2.2 Accessibility

The concept of accessibility has been recognized by researchers and planners as an alternative paradigm that constitutes a holistic approach towards achieving sustainable urban development and mobility management. Accessibility measures provide frameworks that assist in the integration of transport and land use policies and design [4]. Prior to discussing frameworks and their various components, the concept of accessibility as it relates to transport and land use must first be defined. Accessibility can be defined as "an individual's ability to reach desired goods, services, activities and destinations" [8]. Based on that definition, the assessment of transportation systems using an accessibility measure approach is beneficial to highlight existing issues of equity and transport disadvantages. Addressing those issues would help create a more socially just transportation system with fair distribution of and equal access to transportation services and LUDs [2, 8]. It has been also argued that the concept of accessibility does not only relate to the characteristics of the transport system, such as travel time, but also the land use system, such as density. Accessibility can also be related to social goals, such as access to employment, to economic goals, such as access to customers, and to environmental goals, such as sustainable mobility patterns [4, 15]. Cervero [16] and Wixey et al. [17] established this by identifying the several ways that accessibility is used for planning and on how 'accessibility planning' can decrease the negative impacts of a transport system on the environment.

2.3 Existing Accessibility Models

Urban transportation planning has commonly used GIS for its capabilities to manage and integrate data, conduct analyses, and provide visualization. The concept of accessibility is concerned with the spatial pattern and links between activities; thus, GIS platforms are suitable for accessibility analysis [12, 18, 19]. Based on the aforementioned, many GIS-based models and frameworks were developed to provide accessibility measures and analyses, such as: TRESIS model, ACCESS tool, Multimodal Transportation Network model, Land Use and Public Transport Accessibility

Index (LUPTAI). Each of those models/frameworks requires a set of data and has a range of applications.

2.4 TRESIS Model

Transportation and Environment Strategy Impact Simulator (TRESIS) model was developed by the Institute of Transport Studies at the University of Sydney as a decision support system that centres around the interdependencies of transport, land use, and the environment. The model consists of a set of integrated modules that outline an accessibility evaluation framework and utilize road and public transport networks, intra and inter-zonal modal level of service, trip patterns, residential population, socioeconomic profiles of zones, and employment opportunities. Some of the model's applications include evaluating potential new infrastructure, modal ridership, land use policies, and residential density [20]. The model lacks consideration of walking as a commuting mode choice and pedestrian infrastructure within its accessibility evaluation framework.

2.5 ACCESS Tool

ACCESS is an evaluation tool developed by Liu and Zhu [18] that integrates the GIS approach, a socio-economic, transportation and land use database, and an accessibility analysis process. The tool aims to provide users with an integrative GIS-based platform that supports decision making with accessibility analyses for various urban transportation planning applications. There are four main functions of the tool: data preparation, Origin–Destination (OD) formulation, accessibility measurement, and visualization. Based on the outlined functions, the integrated database contains spatial and non-spatial data including trip survey data, OD spatial separation, travel modes and road network, population socio-economic characteristics, LUDs opportunities, and attractiveness of opportunities [18]. The ACCESS tool considers walking as a means to access public transit (PT), but does not consider it as a choice for commuting on its own to access LUDs.

2.6 Multimodal Transportation Network Model

Djurhuus et al. [12] developed a multimodal transportation network model that integrates GIS and PT time-based component aiming to incorporate all stages of PT travel, such as walking or cycling to access PT, waiting for PT departure, in-vehicle transit time, and interchanges/transfers time while determining individual-based accessibility of PT and LUDs. This was accomplished by embedding a PT travel planner, weighted directed graph, and walking time with GIS software. PT accessibility and temporal factors are directly linked, thus, the model uses travel time as the main factor for evaluating accessibility. Typically, GIS network models simplify temporal factors, and the multimodal transportation network model addresses this limitation [12]. The model focuses on PT and does not consider private vehicles, walking, and cycling as modes of transport to access LUDs.

2.7 Land Use and Public Transport Accessibility Indexing Model (LUPTAI)

The Land Use and Public Transport Accessibility Indexing Model (LUPTAI) is a GIS-based accessibility evaluation model that takes into consideration LUDs and road, pedestrian, and PT networks. The developed and inherent accessibility index accounts for degree of choice where walking is considered a transport mode to access LUDs and PT. The model's aim is to provide visual representation of PT and LUDs accessibility by producing maps via GIS application. Data requirements for LUPTAI includes employment, LUDs services (health, shopping, financial, postal and education), road and PT networks, and OD trip surveys. One of the main advantages of the model is that it is open source and can be used with any GIS tool [8]. Private vehicles, community transport, and cycling are not accounted for in the LUPTAI model, which is one of its limitations.

3 Methodology

The methodology to develop the proposed GIS-based Land Use and Multimodal Transport Accessibility Evaluation (LUMTAE) module and integrating it with the existing model includes: (1) conducting a comprehensive literature review; (2) identifying the procedural commonality of the existing GIS-based accessibility evaluation models; (3) outlining the proposed module's development procedure; (4) planning the module's integration with the main components of the existing model; and (5) ensuring that the relationship and interoperability between all the modules is smooth to achieve the set objectives.

3.1 LUMTAE Module Development

Through extensive literature review, the common steps in the development of existing GIS-based accessibility evaluation models were identified and a procedure for the LUMTAE module development was outline. The combined module development procedure is modified to ensure that multimodal transportation accessibility is considered. The proposed module's development procedure will consist of four processes: (1) Data requirements and collection; (2) Data query and retrieval; (3) Accessibility measure selection; and (4) Accessibility calculation and visualization [8, 9, 12, 18, 20, 21]. The processes are merged into two steps: (1) Data requirements and collection, and (2) Module application.

3.1.1 Data Requirements and Collection

Existing models commonly measure accessibility based on walking or cycling distance and vehicular (private and public transit) travel time. Thus, initially it is vital to identify and collect the required datasets to be used by the module. The required data, which include spatial and non-spatial data, is divided into two categories: (i) transportation, and (ii) land use systems. For the transportation systems data requirements, the networks GIS datasets, such as the road, public transit (bus, train, and light rail), pedestrian, and cycling networks, will be obtained from open data available online by the [22] at the provincial and municipal levels. The PT routes, stops, and frequencies data will be extracted from the local PT websites and the various municipal official plan transit priority network maps. The OD survey to determine travel behaviour will be obtained from various municipal transportation planning committee websites. For the land use system, LUDs determining the location of activities and services can be obtained from open data. The missing LUDs can be determined and manually imported by using google maps. LUDs will include employment centres, health institutes (such as hospitals, dentists, etc.), educational institutes (schools, universities, etc.), shopping centres (malls, stores, etc.), and miscellaneous services (banks, post offices, etc.). Zoning/district maps, employment rates, and demsographics data will be obtained from open data available online and from various municipal transportation planning committee websites.

3.1.2 Module Application

After the required data is compiled, pre-processed, and embedded in a GIS database, the module will be programmed to streamline the processes. The data query and retrieval process will support the module's interoperability between the database and GIS tool. The selection process of the accessibility measure will determine the appropriate accessibility analysis approach based on the travel mode(s) under consideration. The accessibility calculation and visualization process will carry out the selected accessibility measure's calculation and provide GIS produced maps to aid users with visualization of the results. Derived from the aforementioned processes, the module will be applied in the subsequent six steps:

1. The network(s) of the selected travel mode(s) are analyzed to determine the level of accessibility to the identified LUDs using the OD zones/districts.

2. If PT is considered as a travel mode in the analysis, the nearest PT stops from the origin are determined during the network(s) analysis conducted in the previous step.
3. The pedestrian or cycling network will determine the walking or cycling distance from the identified PT stops or LUDs, considering individuals' freedom of choice to walk or cycle as a form of commute to access PT or LUDs.
4. Travel time analysis is performed on the appropriate network(s) to identify the LUDs that can be accessed from the origin for a given travel time. Waiting for PT departure, mode transfers, and in-vehicle transit times will be accounted for in the analysis.
5. The computed LUDs' accessibility values will then be interpreted on a GIS rendered map.
6. A multimodal accessibility classification scale will be developed based on the PT accessibility scale devised by Yigitcanlar et al. [8]. Using the computed accessibility index values, a classification of accessibility measure will be assigned to aid users and decision makers in using accessibility levels as a point of comparison for new and retrofitting infrastructure.

3.2 Model Components

The model was initially developed with five modules, namely: (1) a rule-based expert system (RBES), (2) a bridge sustainability rating system (BrSRS) module, (3) a bridge environmental performance strategy mapping (BrEPSM) module, (4) a 3D CAD module, and (5) a cost estimating module. The RBES was developed as sets of IF–THEN rules in an excel database based on the incorporation of two rule-bases: heuristic as rules of thumb gathered from conducted interviews with a number of bridge design experts and algorithmic that consists of the Ministry of Transportation of Ontario's highway geometric design guidelines, bridge structural codes and the navigational waterway guidelines. The conceptual cost estimating module generates the bridge's approximate cost estimate based on the recommended bridge type and its associated dimensions that are determined by the RBES while applying the required time and location adjustment factors. The BrSRS module provides users the capability to customize a sustainable bridge in accordance with the developed sustainability rating system. The BrEPSM module provides users with a preliminary Environmental Impact Assessment, which is relevant for any project's forecasted footprints. And finally, the 3D CAD module renders a model of the proposed or retrofit bridge based on the RBES output [13].

The proposed LUMTAE module will be the sixth module to be integrated into the said model. With the LUMTAE module, the model will permit users to evaluate proposed locations of new bridges and retrofit options, such as adding a transit priority lane, by using accessibility as an evaluation metric. Ultimately, adding the proposed module will provide the model with capabilities for users and decisionmakers to determine the appropriate locations for new bridges, address existing infrastructure design issues, and solve multimodal commuting barriers with respect to accessibility levels. Figure 1 illustrates how the LUMTAE module will be integrated with relation to the rest of the modules. The module will transfer data between the RBES and 3D CAD module as their outputs will be used by the module's data query and retrieval process. Figure 2 illustrates the proposed interface for the LUMTAE module and Fig. 3 depicts the model's logical flowchart that facilitates the development of the user-friendly interface. Moreover, the modules were developed to suit their respective logical step in the model. Each module is represented by the amount of information required to display and the available selections users can perform.

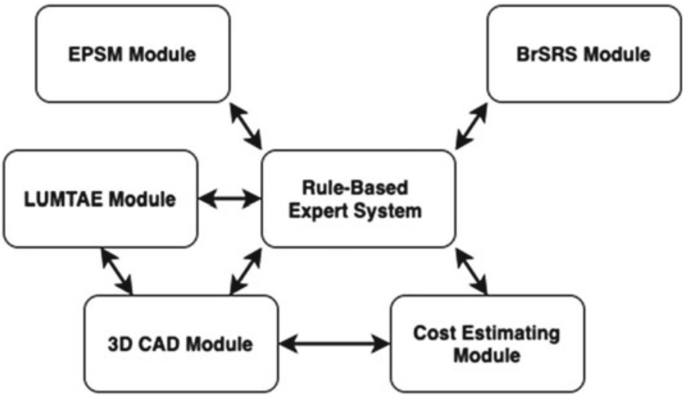

Fig. 1 Model's components

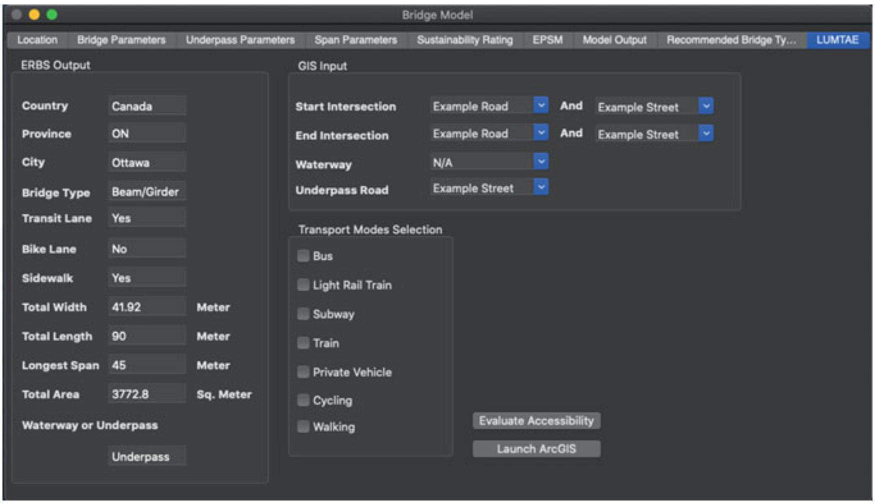

Fig. 2 LUMTAE module's proposed interface

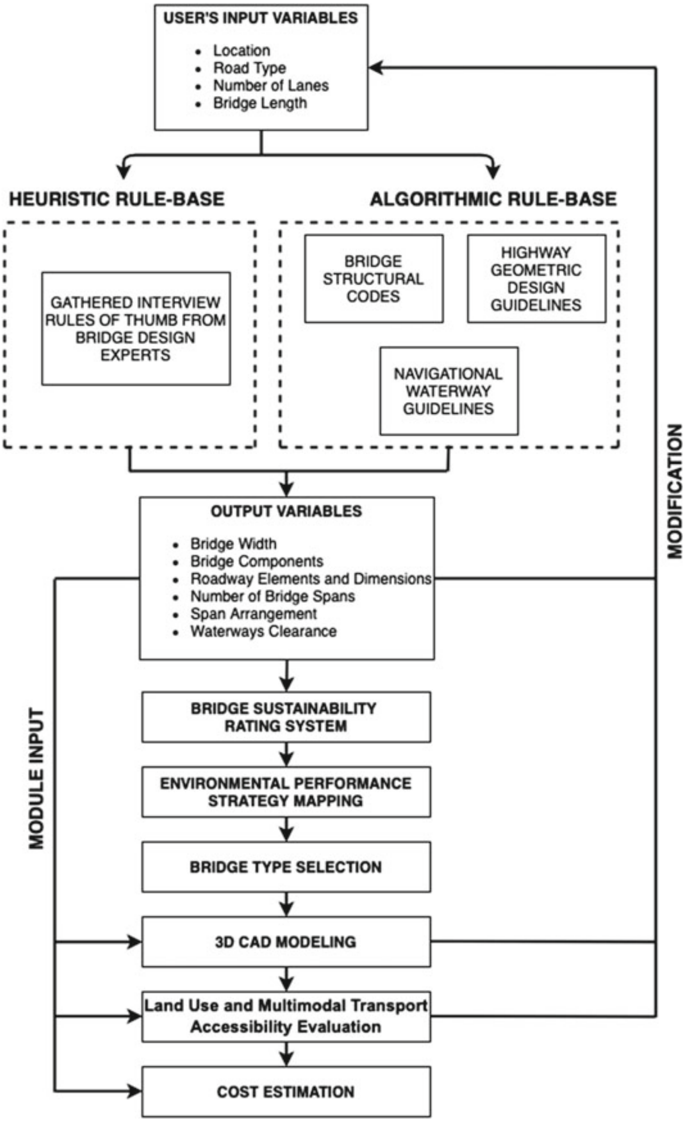

Fig. 3 Model's flowchart

4 Conclusion

This paper describes the proposed development of a GIS-based Land Use and Multimodal Transport Accessibility Evaluation (LUMTAE) module and integrating it with an existing model that encompasses five different modules: a RBES, a BrSRS, an BrEPSM, 3D CAD modeling and cost estimating. The model aims to provide users and decision makers a streamlined approach to quickly prepare designs and generate cost estimates for new and retrofit bridges. The model incorporates a sustainability design approach to provide users with the option to conceptually design either a conventional or a sustainable bridge. The proposed LUMTAE module will be developed to enhance the pre-existing model and will involve four processes, namely, data requirements and collection, data query and retrieval, accessibility measure selection, and accessibility calculation and visualization. The required data will be collected from open data provided by the Government of Canada and compiled in a GIS database, the appropriate accessibility analysis approach will be determined based on the travel modes under consideration, and GIS tool will be integrated to produce maps that assists users with visualizing the evaluation results. The module will allow users to use the accessibility evaluation as a metric to determine ideal locations for new bridges, address existing bridge design issues, and solve multimodal commuting barriers.

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Initial Investigation of a More Sustainable Method for Constructing Electric Conductive Pavement

Mohammad Anis and Mohamed Abdel-Raheem

1 Introduction

Since snow and ice formation significantly affect road traffic safety, it is necessary to keep off the pavement during harsh winter conditions [12]. Over the last few years, different methods are developed to resolve the issue; however, it still requires a more efficient and economical way to remove snow or ice on the pavement for continued traffic flow and ensure road safety. To overcome drawbacks involved with conventional methods, the pavement heating system has recently been studied immensely due to its advantage, including environmentally friendly, economical, and operational sophistication [18]. Many pavement heating systems have been studied in previous research; the usages of the electrically conductive coating or conductive thin film are new [23]. They are formed by dispersing conductive elements in the polymer matrix, which work as a resistive heating medium while applying current through the matrix. According to the principle of Joule heating, the resistor can be heated up when the current passing through it. Therefore, utilizing the conductive coating composite as a resistor by controlling the desired resistivity, which enables generating the required amount of heat to top the pavement surface and use for melting ice and snow from the pavement.

Since the coating has higher conductivity by incorporating conductive materials into the polymeric matrix, which able to carry a sufficient amount of current. Previously, the electrically conductive coating has been utilized for machinery, microelectronics, aerospace, chemical industry, anticorrosive coating, and so on [5, 19], now it is considered widely for thermal management due to having supreme characteristics [22]. To achieve the desirable resistive heating performance, requires an appropriate combination of polymer and conductive materials and which is crucial. Recently,

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S. Walbridge et al. (eds.), *Proceedings of the Canadian Society of Civil Engineering Annual Conference 2021*, Lecture Notes in Civil Engineering 247,
https://doi.org/10.1007/978-981-19-0968-9_8

waterborne polyurethane (WPU) has gained much attention and has been used widely since its lavish properties include flexibility, elasticity, abrasion-resistant, and suitable adhesion with the substrate [13]. Unfortunately, it needs to enhance conductivity because of the higher resistivity of WPU, so it should incorporate higher conductive fillers to improve the conductivity of the composite. The Graphite powder (GP) is considered a suitable conductive filler to prepare polymeric matrix composite due to its applicable conductive property and low cost [6].

This study intends to investigate the viability of using GP-WPU composite as an electrically conductive coating for constructing heating pavement. To this end, conductive coating composites with different fraction volumes of GP and WPU were prepared and investigated their surface heating performance. The expected outcome of this investigation is to depict a guideline for conducting large-scale construction heating pavement applying the conductive coating.

2 Literature Review

In recent years, the electrically heated pavement has gained significant attraction since its great potentiality for removing snow or ice from the pavement and which is assumed more energy-efficient and environmentally friendly than traditional methods. Consequently, some researchers have been studied and lead several ways to develop electrically heated pavement, for instance, embedded heating cable, electric grill, electrically conductive concrete, and electrically conductive coating. Among them, electrically conductive coating or thin film is a new approach and which have several advantages, including low cost, applicable on the existing pavement, and operation sophistication compared to the other alternatives.

In order to make a desirable electrically conductive composite, which should have a sufficient amount of conductive materials along with binders; as conductive materials, various carbonaceous materials have been used in previous researches, such as carbon nanofibers [9, 15], graphene [16], or carbon black [1]. The conductive fillers require to disperse evenly while blending with binders, that creates enough conductive paths inside the composite. Thus, it needed a suitable binder to make this synthesis and ability good adhesion to substrates. As a binder, numerous types of polymer can be used in the composite; for instance, epoxy resin has been used as a binder and applied on the various substrate such as portland cement concrete (PCC) surface [4] and asphalt concrete pavement surface [2, 3]. The polyvinylidene fluoride (PVDF) has been used as a binder to create the superhydrophobic coating on the substrate [9, 21, 25], whereas it appeared low strength and weak bondability. In recent years, polyurethane (PU) polymer has increasingly gained attention as a coating material, since it has a superior binding ability with the substrate. Waterborne polyurethane (WPU) has become popular than solvent-based polyurethanes because of its minimum toxicity that positively affects surface coating applications. Moreover, WPU has elegant properties such as flexibility, abrasion resistance, versatility, and far-reaching substrate applicability [10, 11, 17]. The WPU has been used as adhesives and coatings on different substrates, for instance, plastics, leather, textiles, paper, rubber, and wood [14, 30]. Different conductive fillers, including glass fiber, carbon nanotube, carbon fiber, carbon black, and graphite so forth, were used right into polyurethane material alone or combined to enhance the thermal stability, mechanical toughness, and electrical conductivity of polyurethane-based compounds. Compared to other fillers, graphite (GP) is assumed to be less costly and had an outstanding performance regarding both conductivity and toughness. Graphite powder (GP) with micrometer-sized particles might boost network microstructures channels, which helps to flow current through the composite properly. The composite with WPU and different dosages of GP exhibited excellent electrical property as well as thermal stability.

3 Methodology

The PCC pavement surface is coated with an electrically conductive composite, prepared with waterborne polyurethane (WPU) used as a polymer binder and micrometer particle-sized graphite as a conductive element. This coating able to heating the pavement surface while connecting to the electricity and enabling it to melt snow with less cost. Since achieving the desirable resistive property of electric conductive coating, the required amount of GP dosage is determined using percolation threshold theory The property of heating capacity of GP-WPU coating measured with infrared thermometer by maintaining control parameter. Figure 1 shows the synthesized composite applied on the concrete surface.

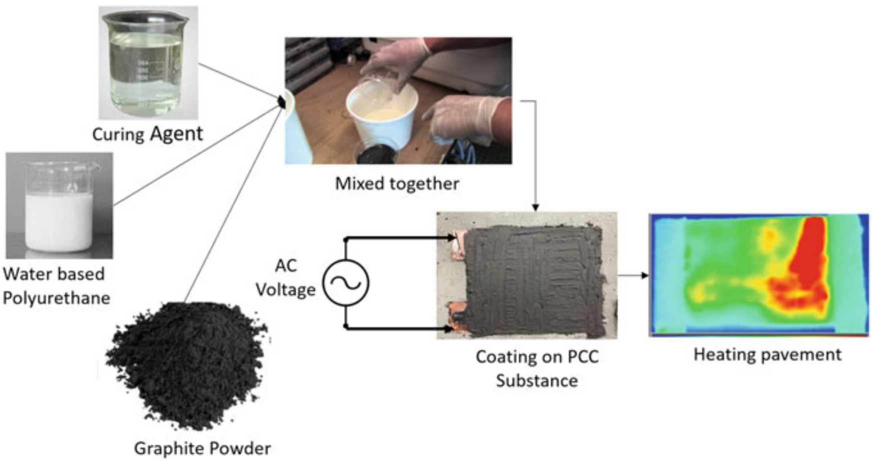

Fig. 1 Methodology of developing heating pavement

3.1 Materials

The conductive filler used in this study was GP with a passing 44 μm diameter, a specific gravity of 2.26, carbon content of 99.35%, and dry-condition electrical conductivity of 28.25 s/cm. The composite coating is supposed to be used on the PCC pavement surface, hence intended for the reducing curing time, which will enable shortening the closing time for traffic on the coated surface. Therefore, instead of incorporating any solvents, this study used fast-drying water-based polyurethane (WPU), which has a low VOC content and eliminates the duration of required evaporation of solvent to set the composite. The WPU by SureCrete was used as a binder with solids content 57%, VOC content 72 g/L, set to touch 6–8 h.

3.2 Application Procedures

For preparing the coating composite, the oven-dried GP was added to the WPU and blend at room temperature for 3 min with 250 rpm speed. Once the mixture was prepared following the procedure, the mixture was applied to the sample surface with a brush. To calculate the applied coating weight on each specimen, required weight records of composite samples, specimen weight before and after applied coating, brush, and mixture pot.

To achieve the desired electrical conductivity of the mixture, required to determine the optimal dose of conductive filler with the polymer content, using a method called percolation threshold, which is an excellent method to explain the electrical behavior of composite [20]. The polymer content acts as an insulator in the mixture, so the volume fraction of conductive filler should be greater or equal to the percolation threshold [9, 24, 28] to achieve its higher electrical conductivity. Therefore, an acceptable amount of conductive filler needs to add with polymer contents, which help to form the continuous conductive paths in the whole matrix or edge to edge. The range of conductive fillers usage in the mixture at which electrical resistivity decreased rapidly, which is known as the percolation transition zone [7]. By increasing the volume fraction of conductive fillers within the percolation transition zone, the electrical resistivity of the composite reduces several orders of magnitude. It continues to reduce while adding more conductive filler above the percolation threshold zone; however, resistivity decreases at a lower rate since the network formation by conductive elements is already saturated in the composite [20]. As the conductive filler dosage continues to increase in the mixture, its viscosity increases, making it challenging to apply to the sample surface [20]. Therefore, it is required to determine the percolation transition zone of GP-WPU composite by containing different volume fractions of GP in the mixture and shown in Table 1.

Two coated substrate samples, such as wood and PCC, were prepared using the mixture proportion given in the table to measure surface resistivity shown in Fig. 1. The wood substrate has been used to measure the electrical resistivity of the surface

Table 1 GP-WPU content for determining the percolation threshold of composite

GP (% Vol.)	WPU content (g)	GP content (g)
0.00	15.00	0.00
2.50	14.63	0.85
5.00	14.25	1.70
7.50	13.88	2.54
10.00	13.50	3.39
12.50	13.13	4.24
15.00	12.75	5.09
17.50	12.38	5.93
20.00	12.00	6.78
22.50	11.63	7.63
25.00	11.25	8.48
27.50	10.88	9.32
30.00	10.50	10.17

since the dry wood has low conductivity, so there was no interference with the resistivity measurement [23]. The coating specimens were prepared on the air-dried PCC surface to simulate the intended real idea during application on the concrete pavements. The final results were prepared by taking on an average of using both specimens, and each type has three replicates. To supply electricity through the composite, the copper tape was placed inside the two ends of the coating as an electrode and which improved the electrical connection since a low dosage of GP could not be exposed to the surface. This study used two probe methods [8, 27] to determine the electrical resistivity, which is more accurate and reliable for measuring surface resistivity of the coating. A digital DC source multimeter was used to measure resistance value with 1 s to avoid polarization [26]. All measurements were conducted at room temperature and relative humidity in the air. Each coating was controlled with the same thickness ensuring at a different point, and width and length measurements of each specimen counted with 0.01 mm precision, that is used to determine the surface resistivity per square by the parallel strip method [29]. The percolation threshold was determined by plotting against (% vol.) to the coating surface resistivity. To relate this result with coated surface heating, performed heating tests on the wood and PCC substrate. The surface temperature rising was measured using an infrared thermometer during AC voltage supplied by the time. Specimens have investigated the resistive heating capability of coating on the PCC substrate were coated with at selective dosages; GP dosage rate was used 2.5, 5, 7.5, 10, 12.5, 15, 17.5, 20, 22.5, 25, and 27.5% volume of the total composite volume, which are selected according to the percolation threshold determination test, and specimens were prepared with three replicates. At different rated voltage with constant 60 Hz AC power supplied through the copper tape and measured temperature rising with an active infrared thermometer shows in Fig. 2e. The measured surface temperature was recorded as explained above for each specimen with a 10 to 30 V AC power supply for 30 min.

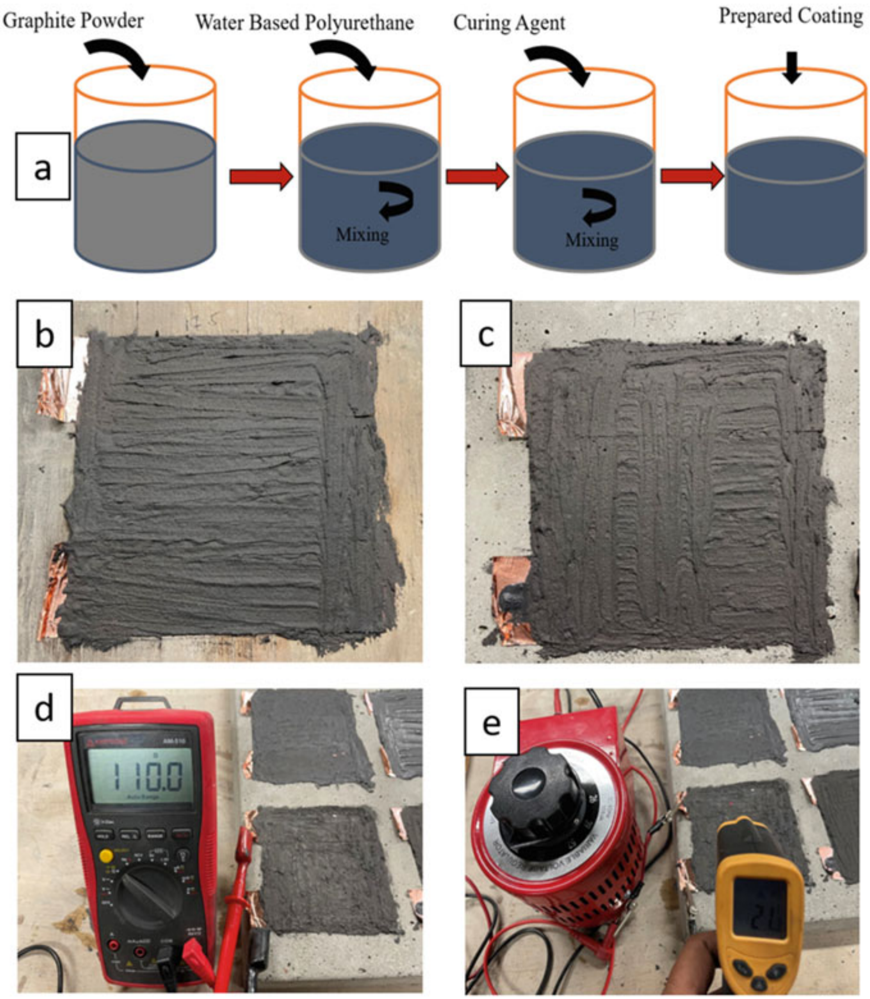

Fig. 2 **a** Preparation method of GP-WPU composite **b** Coating applied on the wood substance **c** Coating used on the concrete substrate **d** Two probe resistance measurement of coating **e** Surface temperature measurement with 64 Hz current supply

4 Result and Discussion

4.1 Experiment Results

The surface resistivity of GP-WPU coating with the different volume fraction of GP results is presented in Fig. 3. As seen in the figure, the GP-WPU composite changed the insulator to conductivity while increases GP dosages rate, which involved different regions, including two rapid decreases and two plain regions.

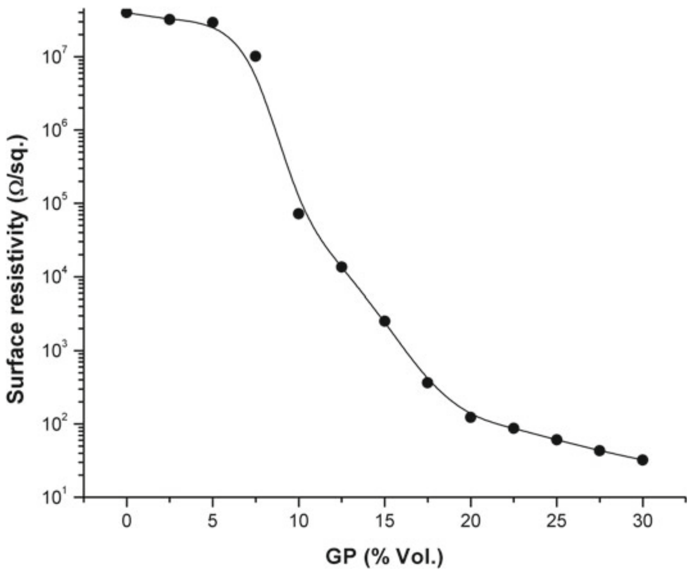

Fig. 3 The variation of surface resistivity of conductive coating with GP(% Vol.) in the WPU polymer matrix

The first plain region was found at 2.5–7.5% volume fractions of GP, which showed the characteristics of forming conductive paths inside the coating and reducing resistivity at a lower rate. The first abrupt changes were noticed between 7.5 and 12.5% volume fractions of GP in the composite, which is shown a transition from insulator to the semiconductor since formed low enough conductive paths inside the matrix. The second abrupt transition was observed from 12.5 to 20% volume fraction of GP, where conductive material containing up to threshold, therefore composite material turns semiconductor into conductive form. After the percolation transition region, observed a marginal decrease of surface resistivity while increasing the GP dosage rate in the composite.

The heating capacity of GP-WPU coatings has been investigated on wood substance after 5 min of the current application. Up to 12.5% GP volume fraction usage coating, no heating effect has been observed on the wood surface while supplying AC 30 V. Above the fraction of volume 12.5% GP, the average surface temperature at the end of the electrical heating test increased containing with GP volume. Figures 4 and 5 present the average temperature rise of coated on the concrete surface while supplying (10–30) AC Voltage with a different dosage rate of GP and investigated with the different time intervals. Each time interval (1, 5, 10, 15, 20, 25, and 30 min) shows a trend of rising the surface temperature along with the increasing GP dosages rate in the composite.

An abrupt heat generation on the concrete surface was observed at 17.5% GP; for instance, when connected 30 V electricity through 17.5% GP coated surface, the average temperature rises a few times higher than the 15% GP coated surface. Up to

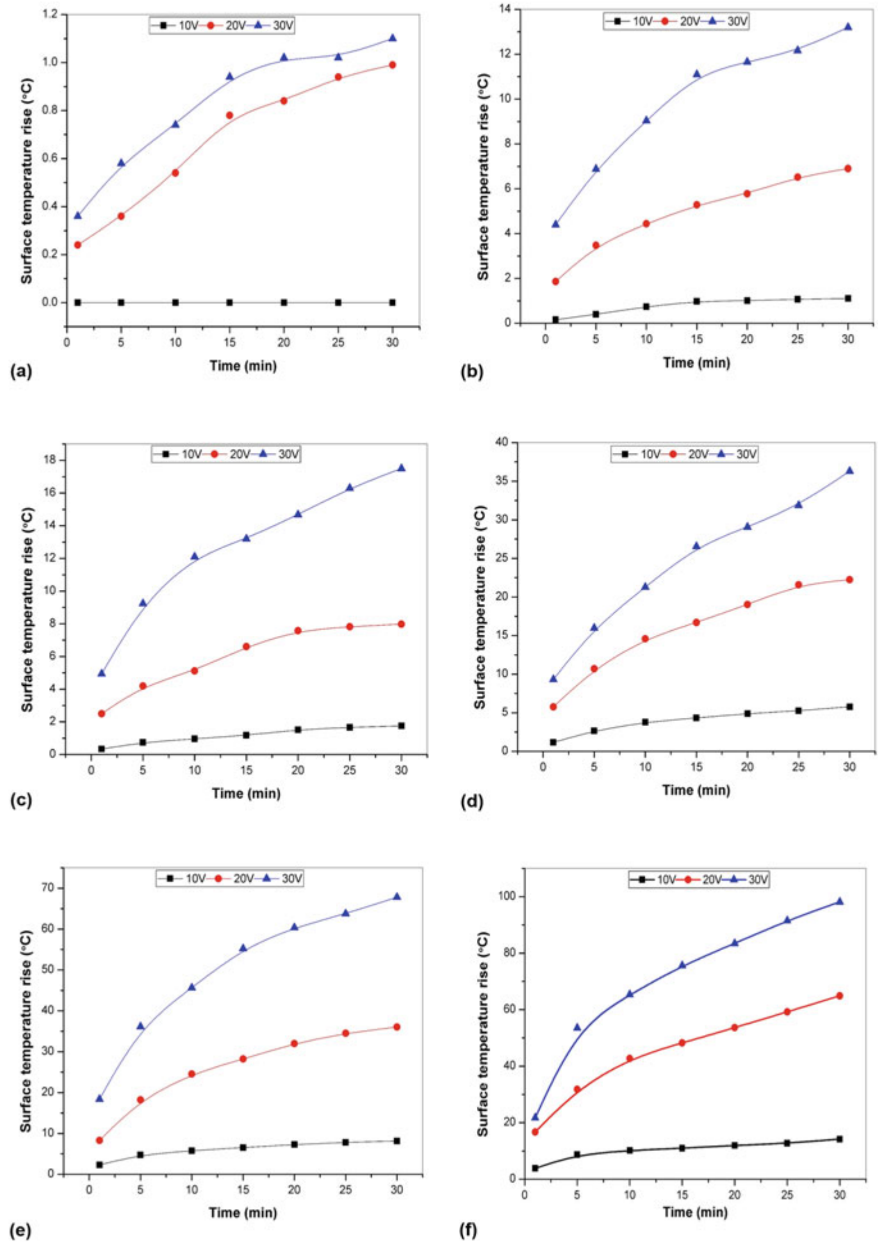

Fig. 4 Average surface temperature rise vs at different intervals of time **a** 15% GP (Vol.) **b** 17.5% GP (Vol.) **c** 20% GP (Vol.) **d** 22.5% GP (Vol.) **e** 25% GP (Vol.) **f** 27.5% GP (Vol.)

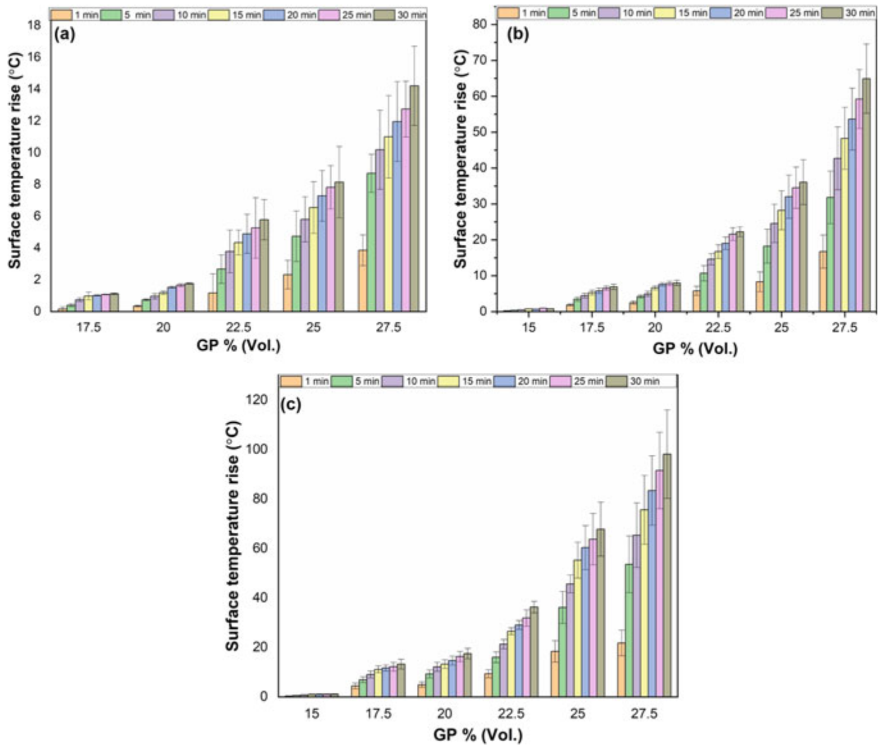

Fig. 5 Average surface temperature versus different dosages rate of GP (Vol.) **a** 10 V **b** 20 V **c** 30 V

22.5% of GP dosages, the temperature distribution on the coating surface was almost uniform, and did not observe any spot extreme heating. Whereas the GP contents at 25 and 27.5% increased surface heat extremely at some spots and somewhere left unheated areas due to converted small fraction of electrical energy to heat energy. Figure 5 shows the relative standard error for 25 and 27.5% higher than the nearest points. Variation of heat concentration at different coating points occurred due to the lack of uniform electrical resistivity of the coating layer that occurred by uneven dispersion of GP.

Above 22.5% of GP contents in the composite, GP is intended to agglomerate in the composite; however, it is complicated to obtain natural characteristics of the GP higher ranges in a small specimen. As seen in Figs. 4 and 5, using the explained composite mixing method of this study, the optimum dosage of GP % (Vol.) greater than 15% and less than 22.5% is considered significant regarding the resistive heating capacity and distribution of heat on the coated surface.

The desirable performance observed GP contains at 20% and 22.5% (Vol.) in the GP-WPU composite regarding average surface temperature rising and even distribution of heat generation. These are attributed to the absence of GP agglomeration, good dispersion of GP through the matrix, and attained lower resistive zones; therefore, the heat distribution was more even by the time. Whereas the coated surface contained greater than 22.5%, the heating distribution was not uniform by the time interval, attributed to increased heat concentration at some points. The GP agglomerated and cannot disperse heat to the nearest point since the lack of good dispersion and continuous heat distribution was more non-uniform by the time. In future, need to experiment with other conductive coating properties such as skid resistance and durability.

5 Conclusion

Electrically conductive coating composites with GP and WPU were prepared with the different volume fractions of GP and applied to the wood and concrete surfaces. After that, this study investigated properties of prepared specimens such as surface resistivity, average surface heating, and heat distribution on the coated area. When GP contains above 7.5%, the coating composite turns insulator to semiconductor, and surface resistivity was abruptly reduced while adding greater than 12.5% GP. Above 22.5% GP dosage rate has tended to agglomerate and started to increase viscosity, and above 27.5% of GP incorporation made it very tough to apply on the surface. The resistive heating test was performed at 30 V on the wood substances for 5 min for selecting the appropriate dosages rate of GP. Later 10, 20, and 30 AC voltages connected with the coated concrete specimen for 30 min, containing above 15% of GP, started to show heating ability and heating capacity intended to rise while increasing the volume percentage of GP. Whereas, above 22.5% of GP incorporation, the heating distribution was noticed uneven during increasing time interval and voltage. The desirable performance was found at 20 and 22.5% GP volume, which is evaluated regarding average surface temperature rise and heat distribution capacity.

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Investigating the Financial Feasibility of Energy-Efficient Appliances Used in Homes

M. Abdel-Raheem, M. Garcia, and M. Pruneda

1 Introduction

The residential sector accounts for 21% of all energy consumption in the United States [18]. In single-family detached homes, approximately 46% of energy consumption is used by refrigeration, lighting, water heating, and other energy-consuming uses [18]. Figure 1 shows a detailed breakdown of energy use in various residential types. As concerns regarding greenhouse gas emissions grow many homeowners are looking towards energy efficient appliances to reduce their primary energy consumption with the added benefit of reduced recurring costs in energy bills.

Programs such as Energy Star provide a label indicating energy efficiency for appliances found to be operating within a defined standard of energy consumption. The costs of efficient appliances are, on average, higher than their traditional (non-efficient) counterparts. Homeowners may hesitate at the higher initial cost and wonder if the accrued savings from lower energy bills can really offset the initial cost of efficient appliances.

The application of the economic method of life-cycle cost analysis (LCCA) is useful in the application of determining the costs associated with projects and their alternatives. LCCA can draw multiple conclusions about the cost effectiveness of various project alternatives such as the total costs associated with project alternatives over a specified period of several years, how long it takes accrued savings to offset initial investment costs, and several other measures. Therefore, LCCA is useful in determining the cost effectiveness of traditional versus energy efficient appliances.

Using requirements and definitions provided in publications from federal government offices and programs such as the FEMP (Federal Energy Management Program) this research will determine the input parameters necessary to complete an LCCA

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S. Walbridge et al. (eds.), *Proceedings of the Canadian Society of Civil Engineering Annual Conference 2021*, Lecture Notes in Civil Engineering 247,
https://doi.org/10.1007/978-981-19-0968-9_9

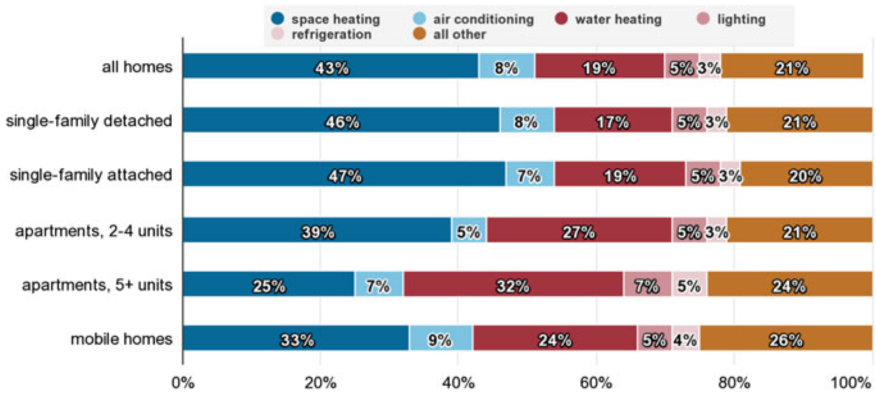

Fig. 1 A bar chart detailing energy use consumption in various dwelling types in 2015 [18]

concerned with the costs associated with energy efficient appliances. The ultimate outcome of the presented research is to present a framework that can be utilized in assessing the financial feasibility of energy efficient appliances versus traditional appliances.

2 Literature Review

The papers contained within the following literature review are concerned with the concept of LCCA and its application in green building, energy efficiency and energy conservation.

This literature review is divided into three subsections, which are: (1) standards and techniques of LCCA, (2) the application of LCCA in green building and product selection, and (3) energy efficiency and energy conservation.

2.1 Standards and Techniques of LCCA

Life-cycle cost analysis (LCCA) is a financial method of evaluating a proposed project and its alternatives to draw conclusions about the cost effectiveness of all considered options [4]. The FEMP's (Federal Energy Management Program) publication on LCCA defines the required input parameters for a LCCA as requiring the following: starting date, service date, study period, treatment of inflation, discounting convention, and energy escalation rates [5]. In addition to these parameters, a bevy of cost data is necessary such as: investment costs, operating costs (not including cost of energy consumption), maintenance costs, energy usage costs, replacement costs, and residual values [6]. LCCA considers the costs incurred throughout the study period and makes predictions about future costs using cost data that is of importance to investors and decision makers [15].

The capital output of the LCCA analysis is the life-cycle cost (LCC). Secondary to this are the numerous supplementary measures which are used to verify the LCC findings as well as add depth to the LCC finding by detailing various aspects of the cost relationships. The "supplementary measures are net savings (NS), savings-to-investment ratio (SIR), adjusted internal rate of return (AIRR), and discounted payback (DPB)" [6]. As life-cycle cost analyses often span many years, this leaves a lot of opportunity for uncertainty in the estimations made by these calculations. LCC is a calculation based on both actual and estimated values which introduces uncertainty, or a source of possible error, into the calculations. This uncertainty may be thought of as an indicator of quality of the data used [16].

2.2 The Application of LCCA in Green Building and Product Selection

LCCA is especially useful in the application of evaluating green building projects, as they tend to be more expensive initially but with reduced future costs (such as reduced utility bill costs). Approximately 52% of homeowners responding to a 2010 University of Nebraska survey stated they would not be able to afford efficiency upgrades to their home [12]. Conversely, there have been other studies that show the premium associated with green or otherwise efficient building practices may be relatively low. Fuerst [3] found that green building could cost only about 2–10% more. Glossner et al. [7] reported that homes with a LEED silver rating were able to recoup their investments in less than 30 years. Furthermore, LCCA has been utilized to evaluate "zero-energy" housing in Australia [10]. The sensitivity analysis conducted by Moore and Morrissey found that by varying key assumptions in the life-cycle costing procedures, zero energy housing could be attained with no additional initial costs as compared to a base case [10]. Another Australian study utilized LCCA to evaluate the use of timber materials in residential building applications to meet green building requirements laid out by the Green Star rating program; this study determined that Radiata Pine was the most cost-effective timber material in nearly all applications except for structural where it was only marginally outperformed by Hoop Pine [17].

In fact, LCCA is so flexible that it may even be applied to the minutiae of product selection as detailed in a literature review conducted in Cabeza et al. [1]. LCCA has been used extensively to evaluate flooring choices. A 2017 study details the development of an algorithm created with the intent of informing decisionmakers about the associated costs of various flooring products [8]. This study found that modular carpet had the lowest life-cycle costs in all considered cost aspects [8]. However, a 2013 study in Australia found that timber floors were the most cost-effective [20].

A Swedish study also found that wood flooring performed most favorably when evaluating environmental impacts [9].

2.3 Energy Efficiency and Energy Conservation

As global populations continue to grow, the demand for energy will continue to increase. There is an inverse relationship between energy supply and demand. As forms of energy, such as coal or fossil fuel start to grow scarce, the cost will exponentially increase as an effect [19]. Energy efficiency and energy conservation are important practices that can decrease energy consumption and allow for dwindling supplies of non-renewable energy sources to be conserved and provide future energy security. Energy conservation is best described as practices/steps that promote using less energy to minimize energy consumption [14]. The purpose of energy efficiency is to use alternative products that consume less energy than those commonly used, such as replacing the traditional, incandescent lightbulb with LED lights.

Over time, energy efficiency has created improvements that have reduced energy use through channels such as efficiency policies, programs, and technologies such as the Energy Star program. Consuming energy with greater efficiency, in turn, improves economic productivity and is a fundamental resource for successful economic well-being [11]. According to Nadel et al. [11] methods for practicing energy efficiency are: (1) the continued optimization of energy-consuming systems, (2) pre-planning to avoid excessive energy loads, (3) promoting generation efficiency, and (4) educating the public on energy efficient behaviors.

If America's adoption of energy efficient technologies continues to increase, energy consumption could be reduced by approximately 17–22% in 2020 and 25–31% by 2030 [13]. To reduce energy consumption at this rate, it is crucial to remember that the residential sector makes up 21% of the total of energy consumption in the U.S. [18]. Several methods have been utilized to accurately provide input from individual households [13]. The ongoing education of homeowners has been encouraged by providing homeowners with thorough electricity bills and recommended residential practices such as: (1) self-reading meters, (2) interactive tools that allow residents to visualize their energy consumption with ease, and (3) home displays that include the ability to compare consumption records [13]. While the reduction of energy consumption is difficult to accomplish, it is also a necessity [2] if we are to meet the reduction in energy consumption estimates for 2030 [13].

3 Methodology

The methodology utilized by this research involved a review of the existing literature about LCCA, energy conservation and efficiency, and the application of LCCA in green building projects and product selection. The literature review provided information regarding the main parameters necessary to conduct a life-cycle cost analysis [5]. Additionally, the literature provided direction in obtaining the discounting rate and energy rate increases as well as the main outputs and supplementary measures necessary for completing a LCCA [5]. This paper's foci are the description of the cash flow model and presenting an aggregation of the cash flow parameters, outputs, and supplementary measures.

4 Model Development

LCCA is dependent upon several different input parameters (cost data, time data, and rates), assumed values (average energy consumption of residents), and equations (life-cycle costs, net savings, and other supplementary measures). Each of these will be discussed in detail within their own respective subsection.

4.1 Study Parameters

The various NIST (National Institute of Standards and Technology) guidelines for performing an LCCA are contained and defined within the following subsections.

4.1.1 Cost Data

The bulk of LCCA is concerned with cost data. LCCA handles two types of cost data: (1) initial or one-time costs, and (2) recurring costs. Initial costs occur at the beginning of the project and only occur once in the study period. In the case of the study of energy efficient appliances, the initial cost will be the cost of purchase and installation of all appliances, whether efficient or traditional. Recurring costs are costs that occur multiple times along the cash flow diagram. Recurring costs may be operation and maintenance costs (OM&R), and replacement costs. OM&R are the costs required of the daily use and upkeep of appliances, excluding energy costs. Each appliance and fixture considered in this study has a unique useful life, after which it would be disposed of and a replacement would be bought. Considering this, the residual or scrap value that the appliances and fixtures retain at the end of their useful life should be accounted for with straight-line depreciation. Lastly, the utility bill associated with energy consumption is another recurring cost. From the point of view of the consumer, the utility costs may be the most important recurring cost as it may be the most expensive.

4.1.2 Rates

There are two rates used for creating an accurate LCCA, (1) nominal discount rate, and (2) energy rate increase. The nominal discount rate is used as the interest rate in the equations for calculating the life-cycle costs as well as all other supplementary measures. This is the nominal discount rate for the base year, this value is easily obtained from FEMP publications. The energy escalation rate is used to account for the increase in utility rates across the study period, the energy escalation rate may be retrieved from the NIST "Energy Price Indices and Discount Factors for Life-Cycle Cost Analysis" publication and from the FEMP's Energy Escalation Rate Calculator (EERC).

4.1.3 Time Data

Because LCCA deals chiefly with money, the study must also ensure that the time-value of money is accounted for. There are various aspects of time that are involved with a LCCA such as (1) base date, (2) study period, and (3) service period. The base date is the start of the project and is the point in time that all project costs are discounted to [5]. The study period is the length of time that costs related to a project and its alternatives are of interest to the decision maker [5]. For a FEMP LCCA, the maximum study period is 25 years. The service period is the period of time that costs associated with daily operations occur. These costs generally begin after the service date, which may also be thought of as the date of occupancy. In other words, this is the period of time in which the recurring costs take place. Likewise, the maximum service period in a FEMP LCCA is 25 years.

4.2 Assumptions

While most study parameter data is concrete, one aspect may remain nebulous- energy consumption. Determining the average amount of residential energy consumption per month over a period of many years is difficult without extensive surveying. The energy consumption in a study such as this may need to be estimated via home energy use calculators from the FEMP or from estimates provided by the appliance manufacturer. When it comes to energy-efficient appliances, particularly Energy Star rated appliances, the average annual energy use can be easily obtained from the Energy Star EnergyGuide, which appliance manufacturers are required to provide. From the information provided on the EnergyGuide label, monthly energy consumption amounts may be easily derived.

4.3 Equations

In order to calculate the life-cycle costs and supplementary measures, LCCA employs the use of many economic equations. Each equation will be defined in the following respective subsections.

4.3.1 Life-Cycle Cost

The first output of an LCCA is the life-cycle cost (LCC), this is the cost of purchasing, operating, replacing, and the discarding of a project and its alternatives over the entirety of the study period. The equation used for determining this cost is as follows:

$$\mathrm{LCC} = \mathrm{I} + \mathrm{Repl} - \mathrm{Res} + \mathrm{E} + \mathrm{OM\&R} \tag{1}$$

As shown in Eq. 1, the LCC is best summarized as a sum of all project costs minus any residual values that occur throughout the lifetime of a project. The first item in Eq. 1 is the *'I'* value, this is the principal or initial investment cost of the project and occurs at time zero on the cash flow. If the initial investment cost occurs at time zero on the cash flow it does not need to be discounted to present-value. The second value *'Repl'* is all replacement costs that happen over the lifetime of the project that have been discounted to present-value. The *'Res'* value is the one piece of cost data that must be subtracted from all other values. *'Res'* is equal to the present-worth of any residual value that is retained by appliances at the end of the project's study period. Residual values are generally determined using a straight-line depreciation basis. *'E'* is the present-value of the monthly recurring cost of energy use, or the energy utility bill. *'E'* must be discounted to present-value using a uniform gradient series to ensure an accurate present-value estimation. The final value *'OM&R'* is equal to the present-worth of any operating costs that are not the cost of energy, maintenance and repair costs incurred over the lifetime of the project.

4.3.2 Supplementary Measure: Net Savings

Net savings is used to verify the findings of the LCC output and measures the present-value costs against the present-value benefits of a project to determine economic performance [5].

Net Savings between project alternatives may be found simply using Eq. 2:

$$\mathrm{NS}_{\mathrm{A:BC}} = [\Delta\mathrm{E} + \Delta\mathrm{OM\&R}] - \left[\Delta\mathrm{I}_{\mathrm{o}} + \Delta\mathrm{Repl} - \Delta\mathrm{Res}\right] \tag{2}$$

Net savings measures the savings accrued by a proposed project alternative relative to a base case. Notably, Eq. 2 is composed of two parts: the first sums the savings of a project alternative relative to a base case, and the second is a sum of additional costs required by the project alternative. 'ΔE' is the savings in energy costs that can be attributed to the project alternative and '$\Delta OM\&R$' is the savings in operating, maintenance, and repair costs. Both 'ΔE' and '$\Delta OM\&R$' can be found by subtracting the present-value of energy or OM&R costs of the base case from the present-value of the respective parameter from the project alternative. In the second part of the equation 'ΔI' is the additional cost of investment as required by the project alternative. 'ΔI_o' is found by subtracting the investment cost of the alternative from the investment cost of the base case. '*ΔRepl*' is the additional cost of replacing appliances and fixtures throughout the study period. '*ΔRepl*' may be calculated by finding the difference between the present-worth of the cost of replacements for the alternative and the present-worth of the cost of replacements for the base case. '*ΔRes*' is any additional residual values attributable to the alternative and is calculated by finding the difference between the alternative's residual values and the base case's residual value as expressed in present-value dollars.

4.3.3 Supplementary Measure: Savings-To-Investment Ratio

The savings-to-investment ratio (SIR) is another measure of economic performance and is a variation of the benefit–cost ratio [5]. SIR is an expression of the relationship of savings to investment. When a project or alternative has a SIR value greater than or equal to 1, it is generally considered to have a preferred economic performance. SIR may be calculated using Eq. 3:

$$\mathrm{SIR}_{\mathrm{A:BC}} = \frac{\Delta \mathrm{E} + \Delta \mathrm{OM\&R}}{\Delta \mathrm{I_o} + \Delta \mathrm{Repl} - \Delta \mathrm{Res}} \tag{3}$$

SIR measures the ratio of savings against investments of the alternative relative to the base case. 'ΔE' and '$\Delta OM\&R$' are the present-worth of the savings of energy and OM&R costs. These values are calculated in the same way as they are for the net savings measure. 'ΔI_o', '*ΔRepl*', and '*ΔRes*' are the present-value of the additional cost of investment, replacement and additional residual value of appliances and fixtures respectively. These values are calculated in the same manner as for the net savings analysis.

4.3.4 Supplementary Measure: Adjusted Internal Rate of Return

AIRR (Adjusted Internal Rate of Return) measures the annual percent yield from the project's investment over the length of the study period [5]. AIRR is a relative measure, so any project and alternatives considered must use the same base date, study period, and discount rates. A caveat of using AIRR is that the project or alternative with the highest AIRR may not necessarily be the project or alternative with the lowest life-cycle cost. AIRR may be found using Eq. 4:

$$\text{AIRR} = (1 + \text{r})\,(\text{SIR})^{1/\text{N}} - 1 \tag{4}$$

Equation 4 utilizes the SIR value as detailed in the previous section. The value of *'r'* is equal to the discount rate used for determining the LCC, this may also be referred to as the reinvestment rate in some publications. The value for 'N' is the length of the study period in years.

4.3.5 Supplementary Measure: Discounted Payback

Payback is used to determine how long it takes accrued savings to "pay back" the initial investment. While there are two measures of payback—Simple and Discounted—discounted payback is the preferred method as it requires all cash flows to be discounted to present-value dollars. Please note that payback is most generally used to identify the benefits of a project alternative where one is clearly more economical than the other [5]. Payback is useful as a supplementary measure for projects where there is uncertainty regarding the project's useful life.

Payback may be found using the following equation:

$$\sum_{t=1}^{y} \frac{[\Delta E_t + \Delta OM\&R_t - \Delta Repl_t + \Delta Res_t]}{(1 + d)^t} \geq \Delta I_o \tag{5}$$

In Eq. 5, 'ΔEt' and '$\Delta OM\&R$' are the present-worth savings in the cost of energy and OM&R at time 't'. 'ΔRes_t' is the difference in the present-value of residual values in year 't' and '$\Delta Repl_t$' is the difference in the cost of replacements in year 't'. 'ΔI_o' is the additional investment cost and *'d'* is the discount rate used for determining the LCC.

4.4 *Cash Flow Diagram*

Cash flow diagrams are used in financial problem solving. The following illustration is a cash flow diagram created for the problem stated in this paper. These diagrams generally have arrows indicating the direction of cashflow as it occurs along the project timeline. Downward facing arrows indicate cash outflow, or cash spent over the project's lifetime. Initial investment cost is represented by a single downward pointing arrow at the beginning of the project timeline. Replacement cost is shown as the downward facing black arrow occurring at N years from the start of the project, this is because the useful life of appliances is not stated explicitly in this study. The final cash outflow is the cost of energy usage, represented by an upward trending blue line. The cost of energy usage increases along the project timeline and is accounted for in the calculations using the energy escalation rate. Upward pointing arrows indicate cash inflow, or cash received from the project. In the case of this diagram,

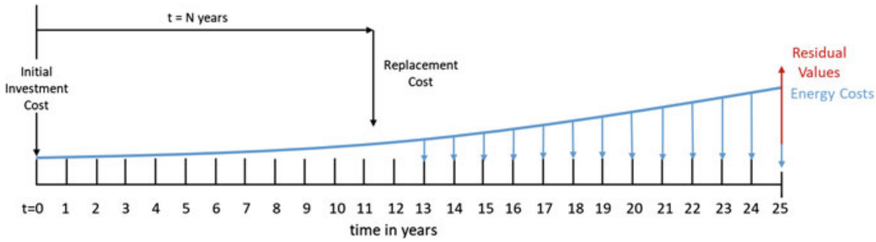

Fig. 2 A general form cash flow diagram depicting the inflows and outflows of cash occurring in a LCCA

the residual value is shown as a red arrow representing the cumulative retained value of all appliances that have not yet reached the end of their useful life at the end of the study period (Fig. 2).

5 Discussion

Each output and supplementary value calculated in the LCCA will be discussed in detail within its respective subsection.

5.1 Life-Cycle Costs

When all present-value costs of a project across its study period are summated the result is a value known as the life-cycle cost (LCC). The project alternative with the lowest LCC is considered the most cost-effective option. All project alternatives must utilize the same input parameters such as base date, study and service periods, and discount rates so that they may be directly compared to one another. Supplementary measures may be used to verify LCC findings.

5.2 Supplementary Measure: Net Savings

Net Savings is a technique used to evaluate the economy of a project and is derived from the Net Benefits technique. Unlike the Net Benefits that measures the relationship between costs and benefits, Net Savings measures the expected accumulated savings from a project over the full length of its study period. Net Savings with values greater than 0 are considered cost-effective, the project with the highest Net Savings will be the same project with the lowest LCC value. Net Savings may only be calculated in respect to a designated "base case" because it is a relative performance measure.

5.3 Supplementary Measure: Savings-To-Investment

SIR is similar to the cost–benefit ratio used to measure the economy of project alternatives. Like the Net Savings measure, SIR is a relative performance measure and must be calculated relative to a base case. SIR's with values greater than 1 are considered cost-effective. It should be noted that the project alternative with the highest SIR is not necessarily the same project with the lowest LCC. SIR cannot be used to choose between mutually exclusive project alternatives.

5.4 Supplementary Measure: Adjusted Internal Rate of Return

AIRR measures the annual percentage yielded from the initial investment in a project alternative. Like SIR and Net Savings, AIRR is a relative performance measure. AIRR is compared against the discount rate used in the LCCA. Economy of a project alternative is measured by how high the AIRR is to the project discount rate, if AIRR is higher than the discount rate the project is economical, if it is lower, it is not economical. Like SIR, AIRR should not be used to choose between mutually exclusive project alternatives.

5.5 Supplementary Measure: Payback

The payback supplementary measure determines the period of time required for accumulated savings to offset the cost of initial investment. Payback is generally expressed in years but may also be expressed in months depending on the length of the study period. Payback, like AIRR and SIR, should not be used to make a selection amongst mutually exclusive projects.

5.6 Statement of Limitations

As this research presents only a framework or preliminary guide for conducting a LCCA that can be applied to energy efficient home appliances there is no analysis performed and therefore no conclusions drawn about the financial feasibility of these efficient appliances. This research also makes references to U.S. government publications and limits an immediate or direct application to international applications and must be adjusted accordingly.

6 Conclusion

With concerns of sustainability rising among the general population, the reduction of energy consumption is one way of conserving and preserving natural resources as well as lowering monthly energy bills for homeowners.

LCCA is an extremely useful method of evaluating products, and projects. By using cost data that is important to investors and decision makers, the calculation of life-cycle costs can clearly illustrate the total cost associated with a particular project and its proposed alternatives. Additionally, LCCA has found a niche in the evaluation of green building design. By utilizing the LCCA technique, an evaluation can be made about the financial feasibility of energy efficient residential appliances.

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Economic Analysis of Water Efficient Appliances and Fixtures in the Residential Sector

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1 Introduction

Only 0.5% of the freshwater on earth is readily available in the form of surface water and accessible groundwater [2]. Therefore, it is important to aid in the conservation of this natural resource, especially as water scarcity becomes an increasing threat in countries around the globe. The best way of conserving this asset is reducing its consumption. In addition to behavioral changes such as flushing less often and turning the faucet off while washing dishes, the employment of water efficient appliances can aid in the reduction of water consumption.

The United States Environmental Protection Agency (EPA) launched the WaterSense program that aims to reduce water consumption through water consciousness campaigns as well as offering a label to appliances and fixtures operating within certain standards. However, for many looking to incorporate these appliances and fixtures into their homes to help reduce their water consumption, the initial costs of these products may cause some hesitation. Despite the promise of future savings in water bills, the temptation to save money at the time of purchase may persuade consumers to opt-out of the water efficient products.

Life-cycle cost analysis (LCCA) is an economic technique that is helpful in determining whether a higher initial investment may be recouped by reduced future recurring costs. By examining various points of cost data, LCCA can make determinations such as net savings, cost–benefit ratio, as well as payback periods to better inform consumers on all costs across the lifespan of a product. LCCA is rooted in sustainability measures, as it was first used by the United States government to evaluate cost savings from water and energy conservation techniques.

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S. Walbridge et al. (eds.), *Proceedings of the Canadian Society of Civil Engineering Annual Conference 2021*, Lecture Notes in Civil Engineering 247,
https://doi.org/10.1007/978-981-19-0968-9_10

This research aims to determine the necessary parameters for determining the financial feasibility of water efficient appliances and fixtures used in the residential sector to reduce the consumption of water. Using guidelines from the Federal Energy Management Program (FEMP) from the U.S. Department of Energy, this research will provide a framework for performing an LCCA on water efficient products.

2 Literature Review

The works presented in this review all deal with the topic of conducting LCCA, water conservation and efficiency, and the applications of LCCA on green building, sustainability measures, or otherwise water-efficient alternatives to a traditional project.

The literature review is subdivided into three sections as to keep related topics together. The sections are as follows: (A) LCCA Standards and Techniques, this section contains information on the process, requirements, and various techniques of conducting a LCCA. The information contained in this section is sourced from a variety of federal and state government publications. (B) Water Efficiency and Conservation, this section reviews literature regarding water-efficiency practices, topics regarding water conservation, and water consumption habits in the U.S. (C) Application of LCCA on Residential Green Building, the final section of the reviewed literature contains the collected works centered on LCCA applied to residential green building projects.

2.1 LCCA Standards and Techniques

The use of LCCA in the government was first brought about by Sect. 4.1 of Executive Order 13,123, for evaluating products, services, construction, and other investments to lower the federal government's spending as well as reducing water and energy consumption [7]. LCCA is useful in the comparison of design alternatives that have differing initial and recurring costs (such as operating costs, or costs of utility bills), and can help decision makers determine which alternative to choose based on the net savings [8]. The primary output value of the LCCA is the life-cycle cost [8]. Life-cycle costs (LCC) are defined as "the sum of present-values of investment costs, capital costs, installation costs, energy costs, operating costs, maintenance costs, and disposal costs over the life-time of the project, product, or measure" [19].

Apart from the LCC output there are various supplementary measures that are calculated in to add nuance and determine the validity of the LCC output. These "supplementary measures are the net savings (NS), savings-to-investment ratio (SIR), adjusted internal rate of return (AIRR), and the discounted payback (DPB)" [8]. Some publications discuss the treatment of uncertainty in LCCA, citing that because these studies often encompass several years that the analysis leaves much room for variation in the estimates. LCCA uses estimated or average values as input, therefore output quality can only be as accurate as the quality of the input data (Stanford University [18].

LCCA is exceptionally well suited to being applied to evaluating building projects. Considering the costs involved in initial investments, operating costs, and utility bills, savings accrued from project alternatives may add up quickly and noticeably. LCCA considers all the costs over the lifetime of a project and generates estimations of the future costs and savings using cost information that is important to investors [17].

2.2 Water Efficiency and Conservation

With an increasing global population and therefore an increasing demand for potable water, prioritizing water efficiency and conservation is more of a necessity than ever before. It is important for humans to start developing short-term and long-term measures that increase the supply of water while reducing its demand [16]. However, resource shortages, aging infrastructure, and population growth has led governments at local, state, and national levels to face utility budget cuts that require the adoption of cost-efficient water conservation methods.

Ratna Reddy [15] suggests that the adoption of LCCA could enhance the efficiency and effectiveness of governmental budget allocations to appropriate departments. In order to adopt this methodology, it would require the assessment of the cost of water consumption supplies in an LCCA framework and the estimation of the expenses of different cost components [6]. The average single-family in the United States consume water both directly and indirectly through appliances and fixtures that have been installed in their residence. Direct water consumption includes water used to drink, cook, and shower, while indirect consumption is the water used in the production of goods and services [20]. The amount of water consumed in a home is dependent on several factors such as the number, age, and water use patterns of the occupants, as well as the appliances and fixtures owned [3]. Additionally, as stated by EPA, "the average U.S family uses approximately 300 gallons of water per day at home", 70% of this water consumption occurs indoors [4].

2.3 LCCA in Green Building and Product Selection

With the rise of efficient and other "green" alternatives has come the belief that these alternatives are notably higher in cost than their traditional counterparts. In the case of green building, this price tag may seem even higher. Niemeyer [14] found that approximately 52% of respondents would not be able to afford energy-efficient changes to their home on their own. However, other studies have found that the cost premiums attached to green or efficient buildings can be relatively low. Fuerst [5] found that the mark-up on green building costs could range from 2–10%.

An evaluation of LEED (Leadership in Energy and Environmental Design) silver-certified homes in Kentucky found that the cost of building and attaining a silver LEED rating had a payback period of less than 30 years [9]. The use of LCCA to evaluate green building design is not without precedent as it has been used to evaluate zero-energy housing in Melbourne [13], as well as a Beijing office building [10]. Despite the high initial costs involved with green and sustainable building choices, in the long run there may be notable benefits in terms of cost savings.

LCCA can also be applied to the process of product selection, a 2014 study details multiple applications of LCCA in product selection [1]; LCCA has seen heavy application in the topic of flooring choice. An Australian study evaluating flooring alternatives used LCCA and found that timber floors were the most cost-effective choice [21]. In 2017 an algorithm was developed specifically for conducting LCCA on flooring products, with the purpose of informing decision-makers about the lifetime costs associated with different flooring types [11]. A study in Sweden using LCCA to evaluate the environmental impact of flooring alternatives found wood to be the best option [12].

3 Methodology

An extensive review of the literature was the first phase of the methodology of this research. The literature included information on the published standards required to complete an LCCA, ways that LCCA has been applied to areas such as sustainable and green building, as well as discussions of water conservation and efficiency. Necessary information such as input parameters, data types, and equations for carrying out a comprehensive LCCA were retrieved from the review of the literature. The literature also aided in identifying the output values and supplementary measures generated by the LCCA process. Using the information collected from the literature, this report provides a detailed description of the model used to conduct an LCCA and offers a succinct aggregation of the outputs, supplementary measures, and parameters.

4 Model Description

The following subsections contain information regarding the required input parameters, cost data, assumed values, equations, and the cash flow used for conducting an LCCA.

4.1 Input Parameters

The LCCA technique requires many input parameters such as (1) cost data, (2) rates, (3) time data, and (4) assumed values. Each will be discussed within this section.

4.1.1 Cost Data

In LCCA there are (1) initial costs and (2) recurring costs. Initial costs occur once on the cash flow timeline, these costs are often the investment cost of the project, in the case of this study: the purchase and installation of appliances and fixtures. Recurring costs are those that occur multiple times within the study period. Recurring costs may be costs associated with maintenance and repair, utility bills, and replacement costs. Finally, the residual value of all appliances and fixtures should be accounted for.

4.1.2 Rates

The first rate considered in an LCCA is the nominal discount rate. This value can be obtained from FEMP or other government publications and is chosen based on the base-year of the study. The nominal discount rate is used to account for interest in many of the equations which calculates life-cycle costs and supplementary measures. The second rate is the utility rate increase, water and sewer escalation rates will be utilized to account for the increase of municipal water and sewage rates over the lifetime of the study. These escalation rates are available from the FEMP publication, "Water and Wastewater Annual Price Escalation Rates…".

4.1.3 Time Data

LCCA is an accurate tool of estimation because it accounts for the time-value of money, therefore there is time data that must be considered. The base date is the point in time that all project costs are discounted to [7]. The base date can also be thought of as the time at which the project "starts". In the case of this research, base date is the time after the purchase and installation of all appliances and fixtures. The next piece of time data is the study period. The study period is the period of time for which the costs are accumulated. For performing an LCCA to FEMP standards, the FEMP recommends a study period of 25 years. Finally, there is the service period. The service period is the period of time for which all costs associated with daily operations take place. FEMP guidelines define the service period as 25 years.

4.1.4 Assumed Values

In conducting an LCCA some values may not be as concrete as others. In particular, water and sewage usage may be difficult to accurately ascertain because water usage can be highly seasonal depending on the part of the country. Due to this variability, water consumption values may need to be estimated with water usage calculators.

4.2 *Equations*

All equations required for calculating life-cycle costs and all supplementary measures will be discussed within each subsection.

4.2.1 Life-Cycle Costs

The life-cycle cost (LCC) is the essence of the LCCA output. The LCC value is verified by various supplementary measures that will be discussed within their own subsections. The LCC is the total cost of a project over the entire study period expressed in present-value dollars. LCC can be found using the following formula:

$$\mathrm{LCC} = \mathrm{I} + \mathrm{Repl} - \mathrm{Res} + \mathrm{W} + \mathrm{S} + \mathrm{OM\&R} \quad (1)$$

Equation 1 is a summation of the present-value of all costs less any residual values occurring along the cash flow of the study period. ‘*I*’ is the present-value of the investment costs, also known as the principal; generally this cost occurs at time zero on the cash flow and thus does not need to be discounted. ‘*Repl*’ is the present-value of all replacements that occur during the study period. The one value that must be subtracted in this equation is ‘*Res*’. This is the present-value of any residual values retained by appliances and fixtures at the end of the study period. The parameters ‘*W*’ and ‘*S*’ are the present-values of the monthly costs of water consumption and sewage usage. It should be noted that ‘*W*’ and ‘*S*’ must be discounted to present-value by using a uniform gradient series. Finally, ‘*OM&R*’ is the present-value of all operations, maintenance and repair costs occurring throughout the study period.

4.2.2 Supplementary Measure: Net Savings

Net savings is a way of measuring the financial performance of a project or alternative. It measures the expected savings of a project or alternative in present-value dollars. Net savings may be found using the following formula:

$$\mathrm{NS}_{\mathrm{A:BC}} = [\Delta \mathrm{W} + \Delta \mathrm{S} + \Delta \mathrm{OM\&R}] - \left[\Delta \mathrm{I_o} + \Delta \mathrm{Repl} - \Delta \mathrm{Res}\right] \quad (2)$$

Equation 2 measures the economy of a project alternative (subscript '*A*') against a base case (subscript '*BC*'). This equation has two parts, the first is a summation of operational savings of the project alternative relative to the base case less the additional investment costs of the alternative compared to the base case. 'ΔW' and 'ΔS' is the savings in water and sewage utility bills that can be attributed to the alternative. Both 'ΔW' and 'ΔS' are found by subtracting the present-value of water and sewage costs of the base case from the present-value of water and sewage costs from the alternative. '$\Delta OM\&R$' is the savings in operations, maintenance, and repair and is found by finding the difference in the present-value OM&R costs between the base case and the alternative. The second part of the net savings equation calculates additional costs related to the alternative. 'ΔI' is the additional investment cost required for the alternative as compared to the base case. The costs of additional replacements attributable to the alternative is given as '$\Delta Repl$' and is found by subtracting the present-value of the replacement costs incurred by the alternative from the replacement costs associated with the base case. Finally, 'ΔRes' is the additional residual values that can be attributed to the alternative. 'ΔRes' is determined by subtracting the present-value of residual values of the alternative from the present-value of residual values of the base case.

4.2.3 Supplementary Measure: Savings-To-Investment Ratio

The savings-to-investment ratio (SIR) is another measure of financial performance. It expresses savings to investment costs (in present-value dollars) as a ratio. SIR may be found using the following relationship:

$$\mathrm{SIR}_{\mathrm{A:BC}} = \frac{\Delta \mathrm{W} + \Delta \mathrm{S} + \Delta \mathrm{OM\&R}}{\Delta \mathrm{I_o} + \Delta \mathrm{Repl} - \Delta \mathrm{Res}} \tag{3}$$

Equation 3 measures the ratio of savings to investments from the alternative (subscript 'A') against a base case (subscript 'BC'). 'ΔW', 'ΔS', and '$\Delta OM\&R$' are the present-value savings in water consumption, sewage usage, and operations, maintenance, and repairs of the alternative relative to the base case, respectively. 'ΔI_o', and '$\Delta Repl$' are the present-value additional costs attributable to the alternative relative to the base case. 'ΔRes' is the present-value of additional residual values associated with the alternative.

4.2.4 Supplementary Measure: Adjusted Internal Rate of Return

Adjusted Internal Rate of Return (AIRR) is another measure of financial effectiveness that measures the yearly percentage yield from the initial investment that occurs over the study period. AIRR can be found with the following formula:

$$\mathrm{AIRR} = (1 + \mathrm{r}) * (\mathrm{SIR})^{1/\mathrm{N}} - 1 \tag{4}$$

Equation 4 uses the calculated '*SIR*' value to determine the annual percentage yield generated by the alternative. The '*r*' value is the reinvestment rate which is generally accepted to be the same as the discount rate used for the LCC. Finally, the '*N*' value is equal to the length of the study period, generally expressed in years.

4.2.5 Supplementary Measure: Payback

The final supplementary measure in LCCA is the payback period. The payback period is the length of time it takes for the accrued savings to equal the initial investment costs. An accurate LCCA should use the discounted payback period as it requires that all costs and savings be discounted to present value. Payback can be found with the following formula:

$$\sum_{t=1}^{y} \frac{[\Delta W_t + \Delta S_t + \Delta OM\&R_t - \Delta Repl_t + \Delta Res_t]}{(1 + d)^t} \geq \Delta I_o \tag{5}$$

'ΔW_t', 'ΔS_t', and '$\Delta OM\&R_t$' are the present-value savings of the cost of water, sewage, and OM&R in year '*t*', respectively. '$\Delta Repl_t$' is the difference in replacement costs in year '*t*' and 'ΔRes_t' is the difference in residual value in year '*t*'. The value '*d*' is equal to the discount rate used in the LCC analysis, and 'ΔI_o' is the additional cost of investment [7].

4.3 Cash Flow Diagram

The cashflow diagram is illustrated below using a general form to illustrate cash inflows and outflows associated with a LCCA. The initial investment cost is represented by the black arrow at t = 0 on the cash flow diagram. Water and Sewage usage costs are shown as two upwardly sloping curves to represent the gradual increase in water and sewage rates as the study period progresses. The replacement costs are represented by the black arrow occurring at t = N years, as each appliance and fixture will have its own lifespan, after which it will require a replacement. The initial investment cost, water and sewage costs, and replacement costs are illustrated using downward facing arrows to represent money spent over the study period, or cash outflow. Finally, the residual value is represented by the red arrow pointing upwards. The upwards arrow represents the retained value of the appliances and fixtures at the end of the study period, or cash inflow.

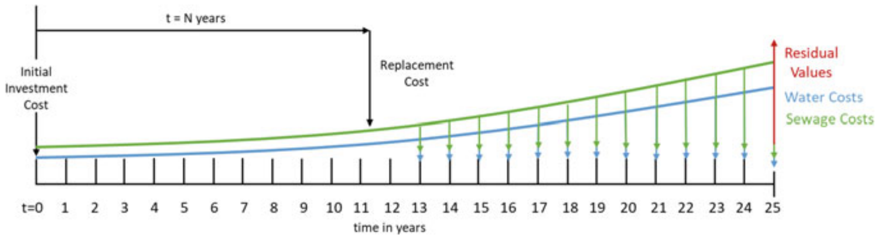

Fig. 1 An illustration of the cash flow diagram in its most basic form

4.4 Statement of Limitations

Finally, the limitations of this research should be discussed. This research is limited to establishing a framework for conducting a LCCA that can be applied to water efficient appliances and fixtures- it does not perform an analysis nor make conclusions about the economy of water efficient appliances and fixtures. As of publication, the model remains untested. Additionally, this paper is focused on the U.S. and references U.S. federal publications for the sources of various financial rates (Fig. 1).

5 Discussion

In the following subsections each LCCA output value and its benefit to the analysis will be discussed in detail.

5.1 Life-Cycle Costs

LCC is the primary and most important output value of an LCCA. LCC is the computation of the present value of each cost that is incurred during the study period by using the Department of Energy (DOE) discount rate then adding those values to each alternative. When comparing various project alternatives, the alternative with the lowest LCC is considered the most cost-effective for the application that is being studied. In order for such accurate comparisons to be made all project alternatives must meet the established minimum performance requirements and must use the same base date, study period, service period and discount rate in their respective analysis. The LCC output values can be verified with calculated supplementary measures.

5.2 Supplementary Measure: Net Savings

Net Savings (NS) is a variation on the Net Benefits (NB) technique of measuring the financial performance of a project. While the NB technique measures the difference that exists between the present-value benefits and the present-value costs for the study period, the NS technique measures the net value of money (in present-value dollars) that a project is expected to save over the life of the study. The NS is a relative performance measure and can only be calculated in respect to a "base case". When comparing project alternatives, the project with the NS value greater than zero is considered the most cost-effective. It should also be noted that the project alternative with the highest NS will be the project with the lowest LCC [7].

5.3 Supplementary Measure: Savings-To-Investment

The Savings-to-investment ratio (SIR) is a variation of the cost–benefit ratio that just as the NS approach, is a relative performance measure. The SIR is a calculation that involves dividing the projected energy costs savings over the finance term by the total cost of the assigned project (including financing, installation, and cost of equipment). Overall, it is another measure of economic performance towards a project alternative that demonstrates the existing relationship of the increased investment cost and savings. A project with a SIR greater than 1 is considered cost-effective [7]. Please note that a project with the lowest LCC is not necessarily the project with the highest SIR. SIR should also not be used to choose between mutually exclusive alternatives as it is more useful as a tool of ranking alternatives.

5.4 Supplementary Measure: Adjusted Internal Rate of Return

AIRR is a method of determining the annual yield from a project's investment expressed as a percentage. Just as the SIR and the NS approach, the AIRR is another relative performance measure. When determining the economy of a project using AIRR it must be compared against the discount rate being used in the study. If the AIRR is higher than the discount rate, a project is economically acceptable. On the other hand, if the AIRR is lower than the discount rate, then it is unacceptable, but if they are equal it is considered to be economically neutral. It should be noted that AIRR cannot be used to choose between mutually exclusive alternatives.

5.5 *Supplementary Measure: Payback*

Payback determines the length of time between the start of the service period and the time it takes for accumulated savings to exactly equal initial investment costs. It should be noted that payback should not be used to select between mutually exclusive project alternatives. Payback is useful for determining a lower bound on the useful life of a project.

6 Conclusion

The demand for water will persist as both the economy and the population continue to grow, making water quality management, water conservation, and reduction of water consumption a growing challenge. The existing literature supports the use of LCCA in the evaluation of green building projects and product selection. This research proposes the use of LCCA to evaluate water conserving appliances and fixtures should be equally appropriate. Adopting the LCCA technique can aid in residential water conservation by providing a tool for use in a comprehensive water resource management program at both the residential and municipal level.

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Towards a More Sustainable Approach to Evaluate Brownfields

Julio C. Constantino and Mohamed Abdel-Raheem

1 Introduction

The definition of Brownfields is any parcel of land, property, or industrial site, with current or derelict conditions that have accumulated over their operational life cycles, unsafe amounts of contaminants, and waste. Contaminants in these sites can pose significant problems, with the proneness of spreading and seeping into nearby communities, the surrounding environment, and being transported through the porous media and groundwater. There is a need to mitigate the spread and impact that these hazardous substances can have on the quality of the surrounding water, soil, and air in nearby communities, which ultimately affects the quality of life for the people and animals near the site. Brownfields are inherently complex, with uncertainties regarding unknown potential risks, decontamination, and regeneration costs, and the legal liabilities imposed on property owners or remediators. Problems along the remediation path create significant delays in remediation efforts and impose an unwillingness by stakeholders and investors to approach these projects as feasible investing opportunities [6]. With an estimated 450,000 Brownfield sites in the U.S., investing in remediation efforts and developing standard proper practices for stakeholder investment approach can prove to be a challenge in certain areas. There is a growing need for decision support in terms of the efforts required for remediation and land recycling. Decision-makers, in this case, must be able to prioritize sustainably and effective clean-up projects to reduce the impact that Brownfields have on the health and wellbeing of communities, successfully reduce the number of Brownfields in the surrounding areas, and minimize the level of contamination present on the site.

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S. Walbridge et al. (eds.), *Proceedings of the Canadian Society of Civil Engineering Annual Conference 2021*, Lecture Notes in Civil Engineering 247,
https://doi.org/10.1007/978-981-19-0968-9_11

Current tools are insufficient for decision-makers to maximize the benefits of remediation projects, typically in the areas of allocating proper resources and selecting priority. To make these decisions, significant consideration must be given to the main frameworks of sustainability, incorporating the main aspects of the Triple Bottom Line is imperative in the decision to achieve the main objectives and ensure that the remediation projects create significant practicality for all stakeholders involved, providing a long-term solution for the future needs of the communities [9, 10]. The objective of this research, in terms of Brownfield remediation and land recycling is to help the decision-makers prioritize which Brownfields to remediate based on the core concepts of sustainability, looking at the environmental, economic, and social frameworks to determine this decision [10].

Brownfield cleanups and remediation efforts offer a solution to growing urban sprawl and support the ability for sustainable and long-lasting community and economic growth [5]. When it comes to Brownfield remediation, clean-up technologies and standards for the project change depending on the contaminants or multiple contaminants located on the site. A recurring problem is that there is no one solution for all problems, and each contaminant requires its inherent treatment and remediation method. With several contaminants affecting different components of the site, a requirement for differing crew and workforce is needed, and varying uses of machinery, for example in the usage of well pumps, transportation for the off-site clean up, or specific requirements for on-site clean up may be required. It is imperative to understand that the usage of manpower, money, machine, and materials are quite important in determining the completion of these Brownfield projects and can also serve as additional standard guides for determining priority selection for future cleanup projects. Oftentimes the limitation of the resources available and the financial capabilities of the remediator, make these assets a crucial and important aspect for the success of the clean-up site. Regarding the necessary funding, the remediator does not have to carry the weight alone, with available funding and Brownfield clean up grants fully backed by the EPA and which can provide several options not just directly involved with the money aspect, several forms of information including literature, knowledge, standards, and tools are available [4].

2 Background

Previous studies have talked about the importance of Brownfield prioritization within various areas in this field. For effective regeneration of Brownfields, various techniques have been used such as Multi-Criteria Decision Analysis (MCDA) and Convex Combination (CC) methodology, with considerable preference laid in the areas of local development potential, site attractiveness and marketability, and environmental risks. With this study, the identification of success factors of Brownfield site regeneration was normally linked to sustainability concepts, whereby the economic, social, and environmental criteria were balanced dimensions in the decision-making process. A necessity for a user-friendly interface and flexibility for adjustment in the criteria for stakeholder necessities and project direction was deemed necessary to be able to take on the complexities involving Brownfield regeneration [6].

Studies in the areas of Brownfield revitalization have also shown a correlation with quantifying the success of Brownfields with relation to the categories of environmental health, finance, livability, and socio-economic indicators, and a study was made through the usage of a multi-attribute decision method which was the analytical hierarchy process (AHP). This research concluded with recommendations for subsequent research, firstly that the risk that factors measured may have received favoritism over other less quantitative but equally important areas of concern. The tool itself should be tested and refined for application on two differing Brownfield sites, with different Brownfield contaminant types and applications. An analysis between the relations among the indicators was also recommended, to verify the success of sustainability claims with direct trade-offs. A recommendation for survey taking was also advised, for a larger pool of professionals. In this research, a total of twenty-one professionals were surveyed [11].

Being able to implement both cost-effective, resource-efficient, and adaptable long-term solutions to similar, albeit different problems, aids towards reliable and effective decision making in the field of Brownfields. Usage of Decision Support Systems (DSS) is imperative in this field, and several examples are available in various other fields that can be properly implemented into the area of Brownfield remediation. Through the usage of *Envision: Sustainable Infrastructure Framework Guidance Manual*, which offers the reader with direction towards systematic change in the planning, design, and delivery of sustainable and resilient infrastructure, several key indicators can be used for the user to determine the best decision parameters and recommendations required when deciding the proper Brownfield site criteria and attributes for decision making in the areas of sustainability and infrastructure requirements. Whereby *Envision* relies on having a total of sixty-four indicators aimed around five distinct categories, which include: Quality of Life, Leadership, Resource Allocation, Natural World, Climate, and Resilience [2]. Looking in-depth at this guide can allow for the implementation of new and well-established ideas that can interconnect and impact the areas of decision making for Brownfield sites, where the areas that should reflect the most impact are taken into consideration when relating to the priority selection process of sustainability of Brownfields.

Within the process of Brownfield remediation, there are a couple of tools and resources available for the decision-maker to make informed judgments based on solid research foundations. The Federal Remediation Technologies Roundtable, established in 1990 and which consists of several U.S. agencies such as the U.S. Department of Energy, NASA, U.S. Department of Transportation, et al. offer private developers with tools, software, the general cost of remediation technologies, remediation standards and procedures, and even Decision Support Matrices for various areas, which can include tools such as: Compliance and Emergency Response, Modeling, Visualization, Geospatial Interpolation and Geostatistics, Risk Assessment, Remedial Process Selection, Cost Estimation, and Cost–Benefit Analysis, et al. With these types of tools, it would seem like Brownfields and Brownfields remediation projects have sufficient initiatives to tackle these problems, but that is not the case. With many Brownfield sites, a lack of money and resources leaves many of these sites in prolonged standby, taking with it many years until enough funding can be collected to finally remediate the problem within these contaminated sites. There are few incentives available for investor approach, but when funding is available it is usually quite competitive. A greater assistance in decision-making is required to aid with the remediation of these Brownfield sites [3].

To be able to prioritize the sites which can have a maximized impact on the environment, economy, and social aspects of the communities is what is currently missing and so desperately required. It is important to minimize the number of Brownfields significantly and sustainably, along with minimizing the level of contamination active within the communities they reside on [1]. The DSS developed in this research will help with prioritizing the Brownfields for remediation based on the mentioned objectives and missing necessities in the field.

3 Methodology

This research involved three main components. The first component was a literature review to determine existing objectives, criteria and attributes involved with Brownfield remediation practices, concepts, and decision strategies, in order to better narrow the most impactful parameters required for Brownfield prioritization. The research included analyzing established and well-known manuals for sustainable and resilient infrastructure, implementing LEED core practices, and gathering information on previous Brownfield studies and research. The second component involved a comprehensive analysis of past decision support systems, which were examined to determine improvements and additions to required parameters and systems. The third component was the decision support tool, which relied on a hierarchy created from the organized data which was collected and gathered to form the objective, criteria, and attribute groups, these components formed to create the hierarchy for decision making for the Brownfield prioritization tool. With comparison to different support systems, the Analytical Hierarchy Process (AHP) was selected as the leading tool for the decision-making process.

4 System Structure

4.1 System Description

This research will consider, from a series of surveys sent to professionals and experts in the field, prioritization of the Brownfield criteria for the creation of a scientific scale developed to reflect the level of priority on the Brownfield site, which will be used to determine and evaluate what Brownfields need to be remediated over others. This

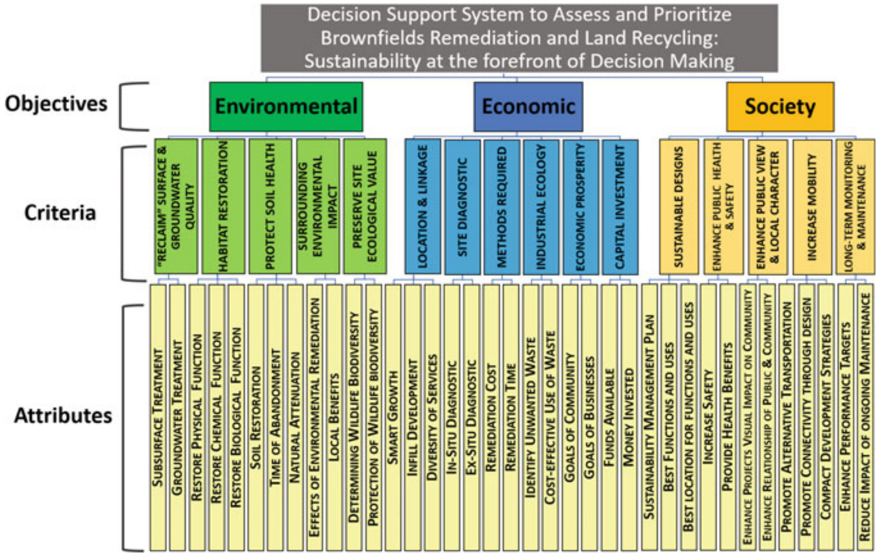

Fig. 1 Hierarchy of Brownfield DSS tool

'scale' will be based on the Quantitative and Qualitative attributes of sustainability. The certain criteria involved with Brownfield sites will be scaled varying in relative importance to the set of attributes, regarding the methods of treatment for the contaminant or multiple contaminants found on a Brownfield Site, level and complexity of said contamination, impacts on the environment, and impact on the communities. This tool will be useful for environmental and governmental entities/decision-makers as well as global clean-up task forces to make decisions on the clean-up priorities of Brownfields with limited funding and manpower. A look into the attributes that will be used to weigh the priority of Brownfields considers the importance of sustainability in the approach. Each of these criteria consists of attributes, on which the importance of the Brownness prioritization tool bases its score.

The system structure that will be used for prioritizing the remediation of Brownfields consists of the following criteria and attributes presented in Fig. 1.

4.2 Environmental Criteria

The environmental objectives consist of five (5) criteria and twelve (12) attributes, which attempt to measure the efforts and remediation process of the site. These environmental criteria will be used in Brownfield's decision making to improve the environmental feature of the site and the criteria include:

- **"Reclaim" Surface and Groundwater Quality** takes into consideration the subsurface treatment, groundwater treatment attributes. Here determining the potential impacts to surface and groundwater in response to contaminants and the impacts adequate remediation efforts can have on the site, some examples of which include using treatment techniques and elimination of hazardous substances, thereby "reclaiming" the quality of the site to a similar state before contamination.
- **Habitat Restoration** takes into consideration restoring the physical, chemical and biological functions of the site, intending to normalize the natural functions of the native habitat. With the attributes, restoring physical function requires returning the disturbed land, back to its natural physical state before toxicity introduction, requiring looking towards certain methods of mitigation such as soil erosion control, soil chemical composition, salt, and nutrient level, soil fertility, soil organic compounds, nutrient specific compounds, et al.
- **Protection of Soil Health** deals with activities used to enhance and restore the soils through both human and natural processes, such as soil restoration techniques, natural attenuation, and site idleness. This is achieved through the usage of soil restoration techniques, and other factors such as natural attenuation and the amount of time the site was left idle.
- **Surrounding Environmental Impact** considers the effects of remediation on the surrounding environment and the local benefits to the quality of land, air, and water that by people and other organisms. Taking into consideration the local benefits of remediation and the global benefit of removal of Brownfield contaminated site from the list.
- **Preserve Site Ecological Value**, whereby a consideration for wildlife biodiversity is established and resources are allocated to protect endangered species in these habitats, with examples including that of national parks, forests, and wildlife refuges. Species conservation and improvement and protection of species through implementing practices, designs, and technologies to account for the protection of local wildlife and fauna, such as maintaining clean water sources and protecting the local ecosystem.

4.3 Economic Criteria

The economic objectives consist of six (6) criteria and twelve (12) attributes, which are used to evaluate the economic efforts and gains from the remediation of the Brownfield site. This evaluation seeks to improve the economic feature of the community and the areas surrounding it and the economic criteria include:

- **Location and Linkage**, involves increasing the sites economic impact on the community with services that are essential or that can support the overall balance of living and housing, choosing options that emphasize development and minimize the usage of existing space from current communities. These impacts can be referred to as smart growth, infill development and diversity of services.

- **Site Diagnostic**, investigating, and testing efforts required to determine the contaminants on the site, the investigation usually consisting of an In-Situ and Ex-Situ diagnostic that involves proper laboratory procedures and site testing.
- **Methods Required**, whereby the remediation cost and time are considered, based on the existing and required technologies available and how critical or widespread the problem on the site is.
- **Industrial Ecology**, whereby the by-products from the remediation efforts are identified and cost-effective disposal is implemented, by which a synergistic approach is taken into consideration.
- **Economic Prosperity**, whereby the goals of the community and the goals of businesses are considered, and an established need is fulfilled without depletion of other resources from the environment or societal aspects.
- **Capital Investment** includes in its decision, the funds available for remediation and the capital funds and money that has been invested through assessments and previous funded effort.

4.4 Society Criteria

The societal objectives include the criteria and attributes that consider the best influence in societal impacts which can be maximized by the process of remediation that the project can have on the community and its people. This evaluation includes five (5) attributes and twelve (12) sub-attributes, consisting of:

- **Sustainable Designs**, whereby the decision-maker considers the best functions and uses for the site location and establishes goals and objectives for the site and determines if the site is the best location for a said objective, with an emphasis on the usage of a sustainability management plan.
- **Enhance Public Health and Safety**, whereby the project can meet the safety regulations for operations and an enhancement and protection of community health and safety is implemented.
- **Enhance Public View and Local Character**, whereby the project seeks to enhance and create significant visual impacts on the community through improvement and remodeling, with criteria involving enhancing project visual impact on the community and enhancing the relationship of public and community.
- **Increase Mobility**, whereby the promotion of alternative transportation practices and connectivity through design is sought up and implemented as part of the compact development strategies.
- **Long-Term Monitoring and Maintenance** includes enhancing performance and minimizing the costs of the social, environmental, and economic impacts of ongoing maintenance through enhancing performance targets and reducing the impact of ongoing maintenance for the site.

5 Model Description

5.1 Model Objective

The proposed model is designed to be used in a hierarchical fashion where the top objective is to prioritize the Brownfield to be remediated. To accomplish this task, each Brownfield is assessed concerning a set of predefined criteria, established in the methodology section, which includes the expert evaluation of the objectives in the field such as criteria weight, attributes-weight, and the final score for Brownfield assessment. Through the usage of the Analytical Hierarchy Process (AHP), the decision centers on the main parameters established and does not deviate towards irrelevant parameters that may stray away from the objective of the research, to prioritize the remediation of Brownfields using sustainability at the forefront of decision making.

5.2 The Analytical Hierarchy Process (AHP)

The (AHP) is a multicriteria decision-making approach, which requires arranging information/criteria such as the goals, attributes, issues, and stakeholders in a hierarchy. Providing the decision-maker with both an overall view of the interlining relationships of the problem at hand, focus and analysis is given to the proposed comparison criteria and attributes of the criteria separately from each pair of elements, the judgment which can be made based on established experience or preference. AHP follows a set of criteria for decision making, and gives importance based on a hierarchy of reported weights and attributes for decision making, the more clearly defined the criteria is, the more thoroughly defined the decision is going to be based on the important parameters that were established at the beginning of decision making, leading towards continued consistency in the decision-making process and avoiding deviation and it is a tool with a range of application used in many industries [7, 8].

Through the usage of an automated user interface developed in excel, and the established process map, located in Fig. 2, the user can pass through the steps of the AHP by answering questions, providing data and specific details of the Brownfield site being evaluated for redevelopment and remediation, and receive the priority for the Brownfield in question.

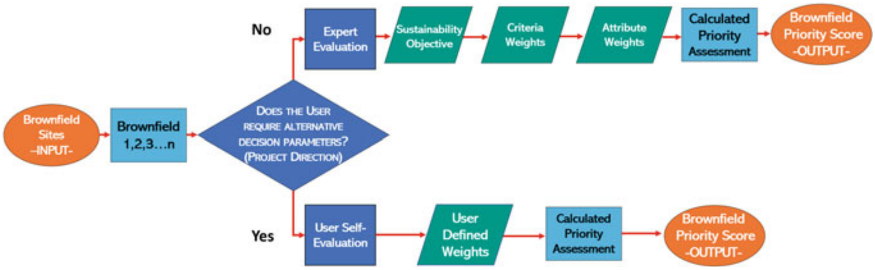

Fig. 2 Brownfield framework process map

6 Example Application

6.1 Modeling and Implementation

An example application was created using the DSS, whereby two hypothetical Brownfield sites were selected to create a real-life simulation of evaluation and decision approach within reasonable parameters of Brownfield sites. A comparison approach is made using the three different sustainability factors, criteria weights and attribute weights, and the proposed weights for each were created from peer evaluation approach and user preference. The example considers a hypothetical real-world scenario of two distinct but similar Brownfield sites, whereby the properties have gone through both Phase I and Phase II of environmental assessment and are awaiting remediation.

For Site A, presented in Fig. 3, site clean-up has not started, redevelopment has not started, and some of the property highlights in its history include the usage of an underground gasoline storage tank in its historical records. Analytical results for soil show elevated TPH concentrations, and the site itself is close to businesses, schools, and an airport. There is no evidence of a rarity of species or fauna in the area. The site resides in an urban community with access to roads, infrastructure and public transportation. An absence of remediation is physically visible on the site and hinders the public view and local health. Several factors are assumed and integrated into the model based on expert experience, personal preference, and general complexity present in Brownfield sites.

For Site B, presented in Fig. 3, the site in question has contamination from landfill use and waste from pharmaceutical applications and subsurface contamination. Site is prevalent with contaminated soil, but it is a considerable distance away from businesses, public facilities, and people. It is located on the rural outskirts, within a large area consisting of agricultural land nearby. There is proof of rarity of species located on the site in the form of a threatened species of coyote that suffers from non-lethal deterrence by farming protection of livestock and pest control. Analytical results show an elevated number of heavy metals around the site, and careful consideration must be given to mitigate the damage above and below the soil surface.

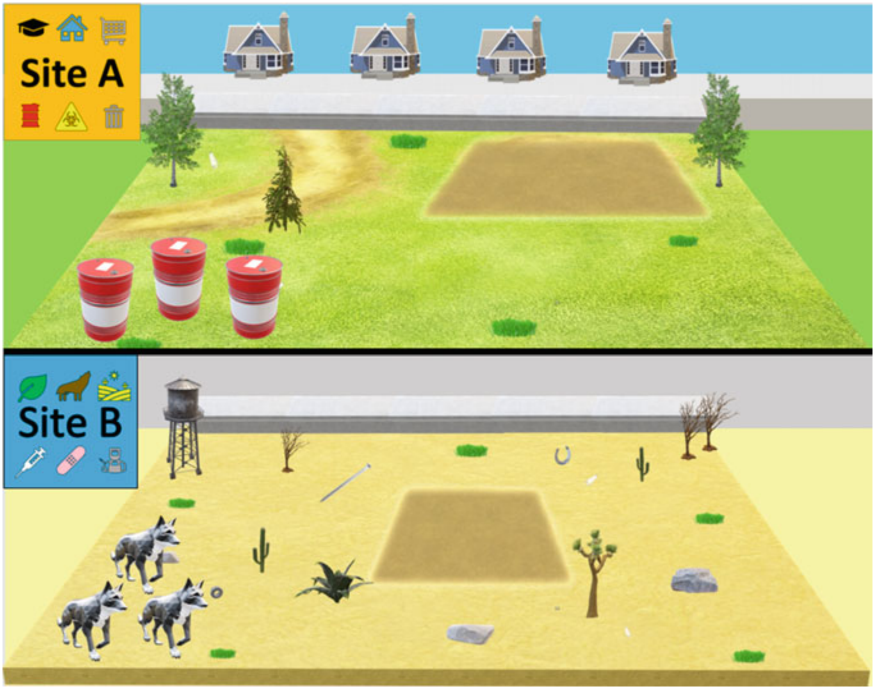

Fig. 3 Site A and Site B—DSS Brownfield example

Several factors are assumed and integrated into the model based on expert experience, personal preference, and general complexity present in Brownfield sites.

A fundamental scale must be used for the user to determine the importance the criteria will have with the final decision output for the tool, in this case, the Likert scale takes the form found in Table 1 and using this scale the user can give weight to the criteria that were mentioned for Brownfields. Along with this, the expert-defined priority vectors are added, based on the survey assessment and results, and are implemented within the tool for use by the decision-maker. Tables 2, 3, and 4 lists an example of the priority vectors regarding the environmental, economic, and social criteria, and an attempt is made to assess and prioritize the Brownfield

Table 1 The fundamental scale for decision support system

Likert scale	Intensity	Definition
Equal importance	1	Two criteria contribute equally to decision
Slight importance	2	Experience favors one criterion over the other
Moderate importance	3	Experience favors one criterion over the other
Very strong importance	4	Criteria is strongly favored over the other
Extreme importance	5	Highest possible approval of criterion over another

Table 2 Priority vectors for environmental criteria

Environmental criteria	Priority vector
"Reclaim" surface and groundwater quality	0.410
Habitat restoration	0.216
Protect soil health	0.180
Surrounding environmental impact	0.061
Preserve site ecological value	0.134

Table 3 Priority vectors for economic criteria

Economic criteria	Priority vector
Location and linkage	0.050
Site diagnostic	0.251
Methods required	0.206
Industrial ecology	0.160
Economic prosperity	0.191
Capital investment	0.142

Table 4 Priority vectors for society criteria

Society criteria	Priority vector
Sustainable designs	0.245
Enhance public health and safety	0.371
Enhance public view and local character	0.181
Increase mobility	0.133
Long-term monitoring and maintenance	0.071

examples using a Likert scale required for measure the intensity of importance in the decision criteria, which can be used based on personal experience or expert decision [8] .

A comparison of each priority vector with each Brownfield site is made depending on user input. Calculation of the Brownfield priority required for the site based on user-reported data, questionnaires, and AHP support using the tool user interface is assumed.

6.2 Results

Pairwise comparisons were conducted for each of the criteria, using the priority vector weights for the environmental, economic, and society objectives. The sustainability objectives carried equal weight when compared to each other, Brownfield priority relied on the criteria comparison. Following the process map, a comparison of the criteria is done for the Brownfields and is presented in Table 5. Implementing

Table 5 Criteria comparison for Brownfield A versus B

Brownfield A versus B	Environmental	Economic	Society
Brownfield A	0.490	0.656	0.755
Brownfield B	0.512	0.344	0.243

Table 6 Final Brownfield ranking—Brownfield A versus B

Brownfield A versus B	Environmental	Economic	Society	Final rank
Brownfield A	0.163	0.219	0.252	0.634
Brownfield B	0.171	0.115	0.082	0.368

the weight of the objectives, Table 6 provides the final rank for the priority of the Brownfields. In the case of this model, it was determined that Brownfield A requires more priority when compared to Brownfield B. The user may also edit the tool based on their desired objectives priority related to either the sustainability objectives presented or personal preference.

7 Future Work

The application of the DSS tool within the realm of Brownfield remediation and land recycling allows the decision-maker to base their decisions under both a reliable and standard approach tool that has been used within various industries, and that has various realms of applications. At the writing for this conference paper, a survey is being developed to be sent to various experts in the Brownfield sector, with a selective approach towards decision-makers affiliated with the reclamation and remediation of Brownfield sites. Along with this, the creation of an excel based user interface, implemented with a decision support tool is in development. The tool will allow the user to either use related data and weights for decision support, able to be edited by the user regarding different project direction, objectives, and requirements. The flexibility of the tool and the criteria weights will allow the user versatility in an already quite complex and hyperactive field.

8 Conclusion

An attempt has been made in this research to critically evaluate the Brownfields using sustainable decision objectives and criteria by implementing LEED and *Envision* core concepts for the prioritization of Brownfield sites. Significant consideration was given in the areas of economic, societal, and environmental aspects of sustainability to aid in the complex process of Brownfield selection for land recycling and remediation. However, the complexity of these projects requires the decision-maker to consider the long- and short-term impacts of Brownfield selection, and in the case of complex decisions, the costs are set aside so that the benefits of the alternatives are properly evaluated. This tool is meant to assist decision-makers and requires the user to have prior knowledge and a significant understanding of the Brownfield site for evaluation. A model objective and usage of the analytical hierarchy process as the decision-making approach was used to allow for the comparison of the influence or contribution of each alternative, both advantageous and disadvantageous to the decision-maker's goals. An example was also provided on the way the tool would work on a hypothetical scenario between two Brownfield sites. This tool allows the decision-makers to be one step closer to the best possible outcome, even with the inherent complexities of the site, an informed decision can be made with sustainability at the forefront of decision making.

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From Collaborative BIM to Value-Driven Asset Management: A Case Study

D. Forgues, A. Motamedi, and M. Boize

1 Introduction

Driven by a major digital innovation, the construction industry is currently facing a profound transformation of its processes. Building Information Modeling (BIM) in design and construction has moved beyond the curiosity stage and is now widely deployed [1]. However, research on the exploitable potential of BIM in the operation and maintenance (O&M) phase is still at an early stage. The restriction of BIM to 3D modeling and 2D plan generation, coupled with the lack of interest in tools and standards for its deployment in facility management (FM), are among the main reasons for its slow adoption [2].

On the other hand, Munir et al. [2] note the importance of being able to measure the added value that BIM would bring to asset owners. Indeed, the difficulty in assessing the commercial value of BIM for FM may well be the reason why its application is so moderately popular. Realizing the financial and organizational benefits that BIM would bring is not a straightforward process for both investors and practitioners. Munir et al. [2] realize that whatever the primary strategic objective of BIM is, the organization must first understand its own capabilities and maturity before it can take advantage of the entire process. An early needs analysis is therefore an important step in understanding which BIM alternative would be best suited to the subject under study.

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S. Walbridge et al. (eds.), *Proceedings of the Canadian Society of Civil Engineering Annual Conference 2021*, Lecture Notes in Civil Engineering 247,
https://doi.org/10.1007/978-981-19-0968-9_12

Even so, the management of facilities requires a closer look. Indeed, it is costly and complex for owners and operators who find themselves having to manage equipment at the end of the cycle [3]. The fragmentation of the different phases of a project and the existing information intensity in the construction sector are identified in the literature as one of the principal problems. Indeed, collecting information to update data models, transferring documents in interoperable formats, accessing the necessary documentation at the right time throughout the project lifecycle, require time and imposes substantial costs. In addition to having to cope with a heavy financial impact, this approach does not guarantee high fidelity in the acquisition of information, since it leaves room for a multitude of errors due to human inputs [4].

The core problem could be the actual business model prevailing for managing real estate portfolios. One proposition is to move from managing building assets to apply an asset management approach to maximize the value of the real estate portfolio. The concept of value creation is an interesting aspect that has not been deeply explored in literature in construction. While value generation is core to the production theory supporting Lean Construction practices, it is mainly focused on the elimination of waste related to non-value-added activities. It is also limited to the realization part of the asset lifecycle. And it does not adequately address waste or value in the information processing.

According to the literature of management, a corporation's only moral obligation is to make a profit, to create value for shareholders. Some authors argue that value must be created not just for shareholders, but for stakeholders since it is morally the right thing to do. It is obvious that there is a lack of attention in the management literature to the main concept of value itself. Moreover, presented models fail to describe how an organization creates value [5].

This exploratory research seeks a better understanding of the concept of value, and how the application of this concept could act as a driver to redefine the industry business model. To achieve this objective the research explores through a case study a new business model based on a value-driven asset management approach. The originality of this case is the fact that the organization under study is operating in a business environment in which competitive advantage is gained through the quality of the facility to provide their customers a unique experience.

2 Redefining the Building Information Lifecycle Around Value

Given that the construction sector spends only 1% of its general revenues on Research and Development [6], its delay in digitization is heavily felt and impacts any process of value creation for assets. Indeed, the management of building assets currently faces major problems: data accumulation in different types of formats, difficult accessibility and reliability of information, significant data loss, laborious data collection and updates [7]. This lack of innovation, compared to other sectors, requires time, energy and money, and results in high cost of maintenance related to poor monitoring of equipment. Building maintenance requirements require a managed approach due to the size of the facility [8]. Realizing the importance of effective and efficient management over the operational life of an asset is necessary to ensure facility sustainability and a satisfactory return on investment. In particular, Pishdad-Bozorgi et al. [1] point out that this is the longest and most expensive phase of the building lifecycle, indicating the importance of proper management.

This ecosystem is data intensive and the greatest challenge in facility management lies in the ability to manage the flow of information generated throughout the entire lifecycle of a project, from the design phase to the O&M phase. The success of facility operations depends entirely on the processes put in place to manage the information. Unfortunately, the traditional method used in construction to collect data, update data, and transfer documents in interoperable formats is overwhelmed by the intensity of information a project generates. The advent of Building Information Modeling (BIM) is a seminal innovation that is slowly changing the process of designing and delivering a facility, moving it away from document to information processing. However, its application is limited to the project. Interoperability with computerized maintenance management systems used for AM is still limited. The advent of ISO 19650 to guide the creation of a Common Data Environment (CDE) encompassing the building asset lifecycle is proposed as a solution to facilitate this need for high quality data. This anticipated virtual environment aims to allow the centralization, accessibility, proper circulation and archiving of information within the team. The principle is that each project participant can use the data stored on the CDE that would be useful for their discipline, and deposit their information in turn. Thus, through the creation of project information, data is stored from the design phase to the construction phase, and ready to be transferred to the operation. Additionally, the integration of all sources of up-to-date data related to the facility will facilitate the creation of a Digital Twin, which replicates the physical facility in a form of an evolving digital entity.

However, as asserted by Winch [9], CDE or digital twins will not resolve the core issue in information processing, since the linear and sequential process of project delivery still creates information gaps which results from loss of value to the end users. In product development, the management of the supply chain and the value chain are closely integrated into a value system. Egan [10] brought the concept of integrated supply chain in the UK construction, but the paradigm of the delivery of facilities as projects is solidly anchored in the industry. Project teams traditionally focus on specification, time and cost, ignoring information needs of the Facility or the Asset Manager, or elements to generate value for the end user [11]. Management of real estate assets is also traditionally focused on reducing costs for operation and maintenance. There is no lifecycle perspective to value creation, and as a consequence, projects fail to generate the expected benefits of their implementation. A proposed explanation for that is the poor understanding both at the project and the AM levels of the means to create value, and little awareness of interdependent changes that are necessary for expected outcomes to be achieved, as well as how the different stakeholders may influence the achievement of projects' expected outcomes [12]. There is a therefore need to move from a cost-based to a value-based asset management ecosystem, a new business model.

As argued by Porter [13] competitive advantage cannot be gained through reducing costs, but by adding value. Value creation is the ability of the components of the value system or chain to work together as a cohesive whole in determining the level of value provided to the ultimate consumer. The problem with the management of real estate assets is that the actual business model is designed to focus on cost in a fragmented way, based on the rationale that reducing the cost of each element of the asset lifecycle will reduce the overall cost of this asset throughout its life. Not only this business model does not achieve its goal to provide a facility at the best cost possible, it usually fails to maximize value for the users of the facility by achieving the best fit for use or for purpose [10].

ISO 55000, a value-based asset management (AM) standard, is starting to be adopted by some large real estate owners. According to the definition of ISO 55000, asset management is defined as “the coordinated activities of an organization for the purpose of creating value from assets”. It aims to balance costs, opportunities and risks against the desired performance of assets to achieve the organization’s objectives. In other words, it is about understanding risk and then developing and applying the right business strategy and the right organizational, process, and technology models to effectively manage all assets [14]. The main breakthrough of the application of this standard for the management of a real estate portfolio is to integrate the project and the management of the facility into one single process.

3 Moving from a Cost to a Value Perspective to Asset Management

While these new standards and project delivery modes provide insights to a value-based asset management for real estate portfolios, literature is scarce about the path to follow to achieve this goal. At the project level, it is proposed to adopt relational contracts [10] such as Integrated Project Delivery (IPD), which emphasize collaboration, transparency, and facilitated data sharing in a managed manner, are seen as beneficial, but not mandatory, for integrating BIM into AM procedures [1]. Some work has also been done to identify challenges of transitioning from traditional to BIM-based processes for AM [15] or the work to be done for an BIM-enabled Asset Management System [1]. A few case studies looked at examples in the industry thriving to find a way to better manage their portfolio by creating some form of CDE [2]. St-Olavs Hospital [16] is a rare example found in the literature of an owner reinventing their business model around what they qualify as an Enterprise BIM. Both the real and the digital built environments with all objects and interrelated objects and processes are connected in a complex interlinked network, realized as an Authoritative Data Source (ADS) in a model server. ADS is defined as the repository or system that contains the cohesive set of data and features that are considered as the primary source for this information and it provides reliable, proper, and secure information to support all business processes within the hospital infrastructure. Moreover, there is one single platform that integrates the project delivery of new assets, eliminating the issues related to facility handover. However, while this represents the finest example of CDE, into a new integrated business model, it does not incorporate the concept of a value-based approach to manage this real estate portfolio.

The originality of this exploratory research is to use an abductive approach to an action research that was focused on the creation of a CDE for an organization which is specialized in wellness health centers to better understand the concept of value-based asset management. The peculiarity of this line of business is that the competitive advantage depends on the organization to realize facilities that will bring the best experience or value to the end users. This case is unique by the fact that the realization and the management of their facilities is the core of their business, and their value system is built around it. This organization (we will name it ABC) built their own AM business model from a clean slate, having no previous experience in managing a real estate portfolio.

4 Research Design

Action research is chosen as the research methodology. It aims to construct and test theory in the context of solving an immediate practical problem in a real-world setting [17]. It is defined by 5 successive steps: diagnosis, suggestion of an action plan, implementation of this plan, evaluation by ABC and specified learning.

Triangulation of data collection techniques (observation, review of documents and interviews) were used. Observation included the participation to design activities such as Big Room sessions, morning Scrum sessions, site visits and team dynamic feedback workshops. Review of documents included, but was not limited to: flow charts, description of processes used, BIM management plan (BMP), list of tools put in place to facilitate operations, and any other documents relevant to the research. Interviews averaging 60 min duration were conducted with the project manager, the director of facilities management and his manager, maintenance operator, and the contract manager. From the data collected and analyzed, process maps were devised and discussed with the team. Then, based on a framework devised from literature, a revised process used the organization as a roadmap to streamline all the initiatives to create a digital asset management environment.

5 A Value-Based Organization Culture and Business Model

ABC qualified itself as "wellness creators". Its mission is to make a difference in people's lives. Therefore, the way they plan, design and manage their facilities revolve around this one single purpose. The culture of ABC, built on shared values, is to continuously reinvent themselves to provide to their clients a rich and unique experience.

ABC is divided into 3 main entities: the management including the client (spa owner), the development team, and the on-site managers. The development team is also divided into two major groups, the information technology/marketing team, and the project team. Interdependencies between these entities is the core of their value system. A constant exchange between the client, the teams in charge of the project, and the on-site managers is required for each new project. Their venue in the real estate market is fairly new, having operated for many years only one facility. An ambitious expansion plan was devised a few years ago, to construct and manage 8 new facilities across Canada.

5.1 The Project Delivery Strategy to Maximize Value to the Customer

What makes this organization approach to real estate original is the fact that these assets are considered as central to the enterprise core business, the facility being the theater in which scenarios are played to achieve users delight, a value proposal centered on the customer experience. This explains the unusual combination of marketing, IT and construction as the development team and also the reason why ABC rejected the traditional business model for the realization and management of their building assets. First ABC could be considered as a project-based organization, constantly adapting and transforming their offer to maintain a competitive advantage. Therefore, it adopted leading edge management approaches such as agile and lean throughout the organization. Also, marketing relies heavily on data to measure the quality of clients' experience. For example, the users of the facility wear wristbands that give them access to their lockers but also to their credit card. These devices allow marketing to track how clients move around and use the facility, how long they stay in a specific space, what they spend and what they spend it on. These data are quite useful in planning and designing new facilities. ABC has also a R&D approach, devising amd selling technologies that enhance the user experience or reduce the cost of exploitation. This is the reason why they rapidly embrace BIM technologies and aim to develop a CDE and adopt a digital twin approach as the backbone for highly adaptative and agile approach to asset management.

The development team realized rapidly that the traditional building project delivery model did not fit well with this organization model and value. Attempts to improve this model, adding an integrated design process failed to offer the expected results. There was a clash between ABC culture of opening, innovation and collaboration and the industry organization of work built around a hierarchy of specialties similar to medieval guilds and the quite low maturity of the industry with IT. ABC development team moved rapidly to adopting emerging delivery strategy based on the Lean Construction Target Value Delivery method and a procurement mode, Integrated Project Delivery (IPD), that better fit their business model. Target Value Design (Delivery) is described by the Lean Construction Institute as a "disciplined management practice that is used throughout project definition, design, detailing, construction, commissioning and activation to assure that the facility meets the operational needs and values of the users, is delivered within the allowable budget, and promotes innovation though out the process to increase value and eliminate waste". Proposed by the American Institute of Architects as a delivery method for BIM projects, IPD requires the contractual collaboration of all parties involved in the project. Indeed, it is based on teamwork that promotes dialogue and transparency through a single contract between all parties. Thus, the responsibilities regarding the risks of failure or success will be the same for everyone. One of the conditions set up by ABC in this procurement process is that the firms they hire must share the same values and desire to innovate.

Carrying out a project in an integrated manner is perfectly integrated into the BIM process, because it involves team members from the design phase to the operation and maintenance phase, and allows digital monitoring of the entire project lifecycle. Few examples of project realization under BIM are currently available, which shows how advanced ABC is in BIM compared to the construction industry. Through this IPD, ABC proposes "Big Room", gathering in the same room all the actors concerned sooner or later by the project, to talk about the progress, the blockages and to build together the short and medium-term schedule. Driven by innovation and a quest for constant improvement, this organization has also experienced a renewal in its project management procedures, by welcoming the agile method at the heart of their processes, which had already proven itself within their IT and marketing teams.

In addition, ABC is in the process of deploying a Common Data Environment for managing their assets, not only for the project, but for the management of the whole lifecycle of their facilities. Digital twin is also an appealing concept since the measurement performance of the various systems is tantamount in this type of environment. They also acquired a requirement management platform that allows the storage and sharing of information, which is centralized in a single location, automatic control of compliance with requirements (coding, content, associated documents and automation of document production).

The ultimate goal is to extend the use of this platform to all their spas. The complexity then lies mainly in the transfer of data from their oldest spa, as the accessible plans are only scanned, and not updated for the most part. Data insertion will therefore have to be done manually, through an on-site inventory. Defining the information requirements in the O&M phase with the technical team, so that they can integrate them from the beginning of the design is one of their current challenges. In addition, ABC is interested in the COBie exchange format and wants to implement it to structure the information and facilitate the transfer of data from Revit to dRofus. This initiative, currently focused on the design team, but will be extended to the operation phase as soon as the information requirements are defined.

5.2 Bridging Theory and Practice

An interesting insight is that, while ABC development team had little experience in construction and asset management, overall, their strategy for deploying BIM-AM in the enterprise seems to be in line with most of the BIM-AM deployment approaches proposed in the literature and in line with the philosophy and principles of ISO19650 and ISO 55000, yet with a business model which is far more agile (since ISO19650 is built on the traditional facility management model of the industry). Figure 1 shows the steps derived from literature for the deployment of an AM-enabled BIM implementation in the organization and compares it to the steps taken by ABC to move toward the implementation of a CDE, using one of their projects as a prototype.

Many positive points are noted, including their decision to move to IPD mode, which significantly promotes the adoption of BIM in all their processes. This mode of implementation is strongly emphasized in the literature, but is at the same time perilous because it is innovative [1]. It is therefore a real risk taken on the part of ABC, which expresses its ability to take the risk by approaching the agile method in parallel. Moreover, a combination of technologies, strategies, and adequate resources, as advised by Giel et al. [18], is found. Indeed, the tools selected, such as COBie, dRofus and CMMS, is a sequence suggested by previous studies [4, 19], because it emphasizes a structured and uniform information management throughout the project lifecycle.

Linking CMMS to the BIM model and Building Automation System (BAS), by including technicians early in the lifecycle in the writing of requirements, is also an approach proposed in various research studies [7]. The proposals are made on the assumption that ABC, following the analysis phase and based on their clearly expressed desire for change, is mature enough to successfully make the transition to BIM-AM. An understanding of the need for technological support and a real involvement of the entire team, from technicians to managers, were retained. This innovation does not upset everyone's roles but offers the possibility of structuring information to work efficiently.

5.3 Discussion and Conclusion

As asserted by many researchers, the issue in the digitalization of the built environment is not technological. While BIM is considered as a seminal, disruptive innovation that was going to create a paradigm shift in the industry, the main barrier to this shift remains its business model, a cost-based mix of medieval organization of work (specialties built on the models of guilds) and mass production.

In order to meet their value proposition as "wellness creators", this organization approach was to grow its organizational maturity, challenging preconceived ideas and practices in all fields and dissolving barriers between specialties. They quickly

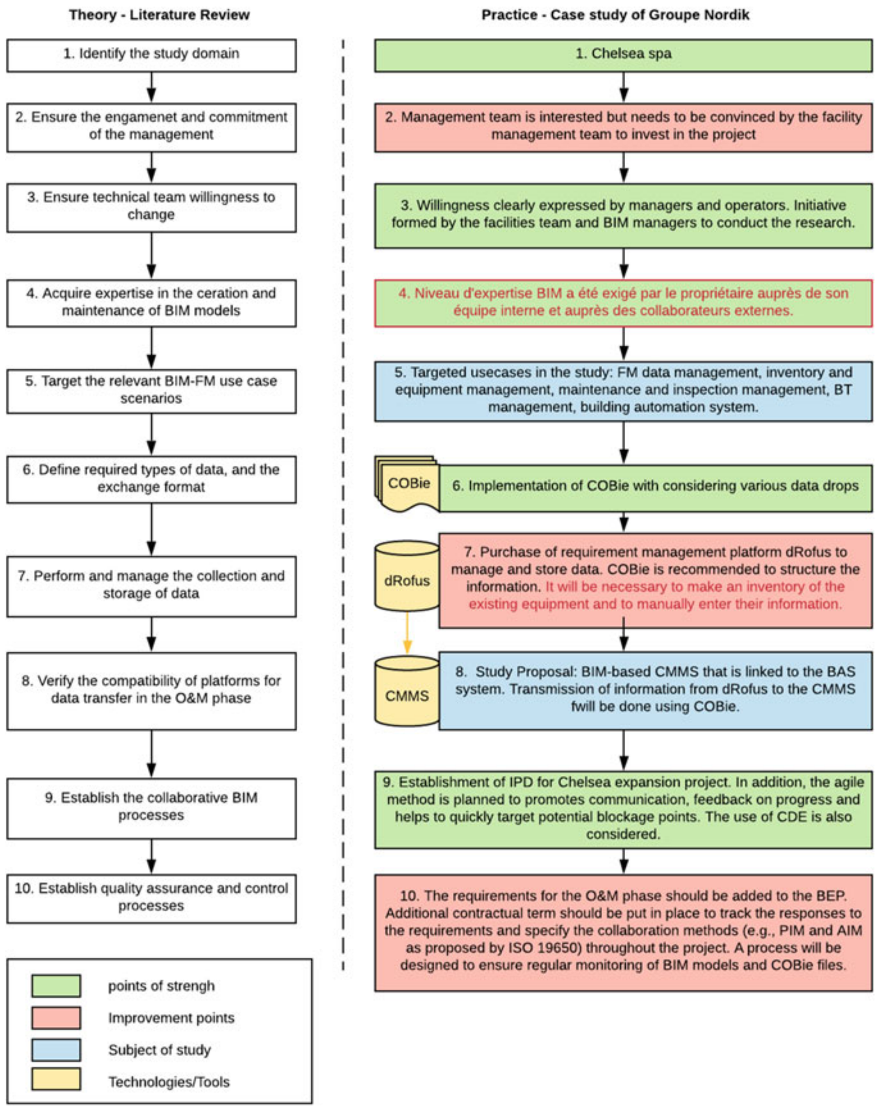

Fig. 1 ABC approach to implement AM-enabled BIM

rejected traditional approaches to plan, deliver and manage buildings as inadequate to fulfill their value proposition to their customers and rapidly seek new ways for achieving their goal. IPD was rapidly adopted because it fitted their value and culture. They adopted BIM because of the opportunity it offered to visualize how the spatial setting could enhance the client experience, challenging the way design professionals work. Methods and tools to stimulate innovation and creativity were welcome from all disciplines (marketing, IT, operation) in a flat organization structure.

The initial objective of this action-research project was to propose an integration of the BIM technologies, BAS systems and Internet of Things into a CDE and digital twin. The roadmap derived from is by itself a contribution. However, digging through the investigation phase of this research, the level of innovations observed in this young organization was intriguing. It raised the question. What was driving such a level of innovations? The answer could be found in literature in marketing and from activity theory. The purpose of this organization is to create value for their customer. All their activity system is built around it, making this organization extremely agile to integrate the best practices and technologies to achieve this goal.

The main contribution of this research is opening new grounds with a proposed theory of new value-based asset management business model for real estate and its empirical validation through a case study. The literature in construction regarding value is mainly based on the cost-based delivery paradigm (value analysis and value engineering). Literature in Lean Construction shed some light on the application of the concept of value-based approaches in the design and delivery of buildings, but fail to provide a lifecycle perspective and the concept of value is not well defined. However, as an exploratory research, it has major limitations, and further research is required. Literature in management and marketing science—which will provide some insights to better understand how value creation—could be applied as a driver for a much-needed paradigm shift in our industry.

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Information Management in Off-Site Construction: Case Study of Mid-Rise Building Construction in Québec

Virginie Messa, Ivanka Iordanova, and Carlo Carbone

1 Introduction

Compared to the overall economy's productivity, construction productivity has been declining over the past decade. The definition of how to improve productivity is a reduction of the waste of resources including cost, time, and skilled labor force [1]. According to Barbosa [2] off-site construction (OSC) is the means that will help to increase by 5–10 times industry productivity. By assigning some parts of the construction industry to a manufacturing-style production system, OSC can optimize the available skilled workforce, leading to a considerable reduction of project duration while improving on-site execution, procurement, and supply chain management.

Whether named modern methods of construction (MMC), industrialized building systems (IBS), prefabrication, modular construction or panellised construction, interest in OSC has been steady and growing since the turn of the century within the architecture, engineering, and construction industries. Hosseini et al. [3] reveals a wide range of research areas explored during the last decade, such as innovative materials (precast concrete, cross-laminated timber or CLT, reinforced concrete and modules), structural analysis, design optimization, sustainable development, design for fabrication, project management and computer-aided design. The wood industry stands out for its ability to combine innovation, sustainability, and efficiency. This renewable material is a potential candidate for automated fabrication in construction and contributes to carbon storage, both of which align with global commitments to reduce environmental impacts of industries [4]. The common vision of the *Société d'Habitation du Québec* (SHQ) and the Quebec Wood Export Bureau (QWEB) is

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S. Walbridge et al. (eds.), *Proceedings of the Canadian Society of Civil Engineering Annual Conference 2021*, Lecture Notes in Civil Engineering 247,
https://doi.org/10.1007/978-981-19-0968-9_13

to establish high-performance living environments that guarantee quality, competitiveness, and sustainable development. Although OSC presents several benefits, its higher cost compared to traditional construction methods for larger scale buildings limits its implementation to the single-unit housing sector in Québec. The objective of this study is to investigate the factors that cause cost overrun issues for larger scale (mid-rise) prefabricated buildings in Québec's construction context. The main reason for targeting mid-rise building lies in the increasing housing demand in the region and compliance with regulations on lightweight wood uses in building construction. The remainder of the paper is organized as follows: presentation of OSC core concepts and the research gap, the research methodology and project description, findings and discussion, and the last section concludes the study.

2 OSC: General Concepts

Off-site construction refers to the preassembly or fabrication of building systems in a factory environment prior to their installation at the project location [5]. Various production systems have been developed for OSC implementation. The literature reveals different ways of classifying OSC systems depending on the degree of on-site labour, the size and shape or the complexity of prefabricated components [6]. Gibb and Frank [7] produced a categorization of those systems, summarized in Table 1, in which OSC is divided into four levels, each level is associated with the type of off-site work. Other authors provide different semantics for each categorization.

The two main areas of OSC that construction projects have benefited from are materials and processes (Kagioglou et al. 1998). A higher standardization of products has been the main driver of OSC hardware aspects. The extensive use of standardized products in OSC has the benefit of helping to avoid delays and re-work [8]. Material innovations have focused on innovative components such as cross-laminated timber (CLT), structural insulated panels (SIP), prefabricated facades, and prefabricated bathroom units or pods. Due to its sustainability and flexibility performance compared to other materials, timber lends itself well to the deployment and application of OSC [9].

As for the operational and process facets of OSC found in the literature, Sardén and Engström [8] presented OSC's ability to reduce the impact of conflicting interests compared to traditional on-site construction because part of the work is relocated to a factory. From a client's perspective, the responsibility for integrating the different project actors and both the design and construction processes are shifted to one company. OSC integration reduces the impact of conflicting interests and makes it easier to manage and control the project efficiently. Moreover, the benefits of OSC can be further enhanced if coupled with the principles of design for manufacturing and assembly (DfMA) [11]. The DfMA approach aims to eliminate waste or any activities that do not add value and to facilitate the manufacturing of a product, its delivery, and its assembly [12]. DfMA leads to the involvement of suppliers, contractors, sub-contractors, and other specialists in the design phase to merge information for

Table 1 Offsite categories from Gibb and Pendlebury [10]

Categories	Definition
Components	Simplified building elements like stairs, trusses, windows, doors. They are not part of the primary building structure
Panels	Non-volumetric elements used as structural frames or building envelopes. Their flat shapes are easy to transport
Volumetric	Units that enclose usable space providing facilities or services that support household activities. Generally, kitchen, bathroom(s), laundry room or mechanical Also named as service core or pod
Modules	Manufactured units that constitute the entire living and service spaces of a dwelling. They are fully prefabricated and simply need to be connected to the on-site structure

efficient project delivery [13]. Indeed, this is necessary to produce precise plans and specifications and to ensure consistency between the prefabricated modules and the expectations on site. Precise planning makes it possible to take advantage of the full potential of prefabrication, which includes favorable working conditions and better-quality work control. This collaborative management approach streamlines OSC design and enables an efficient collaboration throughout the project.

The adoption of OSC is low, despite its well-documented benefits. The working paradigm introduces by combining informal and error-prone communication channels from construction [14] with OSC specified and repetitive systems [15] causes higher construction costs. This could be the reason for the low adoption of OSC processes in the industry. In addition, the Construction Industry Institute estimates that between 25 and 50% of construction cost overruns are due to information errors during the design stages. Cost-related issues are surging in the construction domain and even more so in OSC projects [16]. The investigation of the causes of cost issues is the objective of this study. The study focuses on mid-rise wood prefabricated buildings in Québec.

3 Research Approach

3.1 Methodology

This research uses a case study approach and a qualitative research methodology. Two reasons brought about this choice. First, a case study not only describes the visible and obvious components of a problem, but it can also help to interpret their underlying meanings and identify interrelationships [17]. Second, Koskela [18] shows this approach as the most appropriate methodology for construction management studies because it offers a deeper understanding of problems in a complex context such as the construction sector, which is highly fragmented. The case study approach includes three steps: project identification, data collection and data analysis.

3.2 Case Description

The case study used in this project consist of two residential buildings of four and six-floors, each with two-level basements, which are used for parking. Each floor includes 3 1/2, 4 1/2, 5 1/2 and 6 1/2 apartments. The prefabrication system used is a volumetric service core including a finished bathroom, 3 wardrobes, kitchen cabinets, counters, sinks, faucets, and mechanical, electrical and ventilation shafts. The team chose a prefabricated service core system to limit the on-site work and speed up construction.

Project management was organized in design-build mode. This means that the client awards a single contract for the design and construction of the work to one party, which in this case is the developer. In addition, it was required that an Integrated Design Process (IDP) be adopted which, by initiating discussions between the various stakeholders early in the design process, allows for important decisions to be made at the onset, which can contribute to lowering costs.

3.3 Data Collection

Data collection was achieved through in-depth interviews of stakeholders involved in the chosen project. Prior to the interviews, an extensive literature review of OSC management was conducted to establish the initial hypothesis. Then questions were formulated to conduct a preparatory interview with the architect working on wood prefabricated systems in Québec. This interview helped to better orient the questionnaire. Once elaborated, the questionnaire was submitted to the stakeholders involved in the design stage to understand the implementation challenges of prefabricated wood pods in large-scale projects in Québec. Semi-structured interviews were conducted with the participants, who consisted of an architect, structural engineer, developer, manufacturer, and the client. To preserve the identity and confidentiality of the persons from whom information was collected, a code was assigned to each participant. Architect (AR), engineer (Eng), general contractor (GE), client (GRT) and the manufacturer (Man).

3.4 Data Analysis

Selecting an analysis unit is the first decision to make when using qualitative content analysis. The unit of analysis can be words, sentences, paragraphs or an entire text, and its determination mainly relies on a research context (Downe-Wamboldt 1992). For this analysis, given that data are collected through interviews, the analysis unit is a sentence.

Then, analysis begins with the coding and the creation of categories based on a careful review of the interviewee's transcripts. The process was facilitated by using a developed codebook to capture the perceptions of key stakeholders. Each interview was carefully reviewed by three research team members to capture information, and the collected data were recorded in each category.

4 Findings

All interviewees agreed that cost overrun was the major constraint to the realization of this OSC building project. Four main categories were identified as cost barriers during the design stage. These categories are: the poor communication between stakeholders, the multiple innovations including modular OSC, changes in the manufacturer's responsibilities in the project, and insufficient information management.

4.1 Communication Issues

Despite the IDP implemented for the project, according to the participants, poor communication between stakeholders remains an aspect that contributes to the cost issue. GE revealed that he did not know what tasks he had to do when the service core would arrive on site, so the estimation was not effective. In addition, Eng noted that since the pods are manufactured in the factory, the reengineering and operating costs to produce the pods must be taken into consideration during the estimation. Reengineering costs may represent between 5 to 50% of the project design costs and can lead to overruns when not properly evaluated. However, the stakeholders were not aware and did not have the necessary information to define these costs.

Another relevant communication issue was that the expectations of the stakeholders were at odds. The client expected the project cost to be lower than traditional construction the professionals, since it was an innovative project, fully expected that there would be cost overruns. This finding is consistent with the literature in which [19] states that unless clients understand offsite processes, their misunderstandings and prejudices consistently lead to lower prefabricated implementation.

4.2 Multiple Innovations Including Modular OSC Systems

The local industry lacks experience with mid-rise prefabricated building projects. Therefore, many technical innovations had to be developed along with the design, even if they were not initially accounted for in the project. The pod used in this project was designed for a single-family house and modifications would need to be made for it to be used in a larger building. As mentioned by AR, it takes a factory visit to understand the process of pod fabrication and to establish the required modifications. Consequently, this represents more design hours, and in turn, a higher design cost.

To shift from single-unit house (single unit pod) to a larger building (multi-storey pods), several parameters must be considered, such as access management, quantity and recurrence of units, and the position of the prefabricated system within the building, as well as mechanical, electrical, and plumbing connections on both sides and on the top and bottom, and the air sealing of the prefabricated system prior to its installation in its final position. Figure 1 presents the difference between a single-unit pod and a multi-storey pod.

Other than the new pods for a multi-residential mid-rise building, other innovations were expected from the team, including the design of a high-performance building from eco-energetic point of view with a level of performance less than 50 kWh/m^2 of living floor area in heating over a full year, which would be an improvement of more than 50% over the Code for an average single family home. The client aims to reduce thermal bridges, optimize fenestration and promote the use of a heat recovery ventilation system.

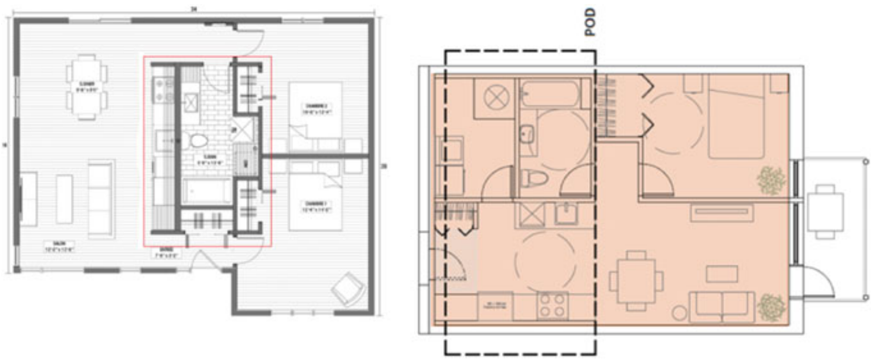

Fig. 1 Diagram illustrating a single unit pod (*left*) and multi-storey unit pod (*right*)

4.3 Increased Responsibilities of the Manufacturer

Compared to traditional construction projects, the manufacturer's responsibilities are greater in prefabricated projects. From playing the role of a supplier, the manufacturer now becomes a main actor of the design process, as AR declared. This is because the manufacturer is now responsible for most of the project components from the pod size to all the furniture (which are included in prefabricated systems) and the assembly methodology on site. These criteria influence the construction methods to be adopted, the energy efficiency of the building and its estimate. These are the tasks for which the manufacturer becomes responsible, instead of the general contractor. This change is brought about because of OSC use in this project and it places the manufacturer at the center of the processes, as mentioned by the client, "the manufacturer is the main player in the project". As a supplier, he did not have the necessary capabilities to respond to these new responsibilities, as the architect points out, "it was during the project that they realized the challenges of building a multi-storey pod". The client also states, "our manufacturers are not familiar enough with multi-storey pods". This change introduces variability, which in turn runs the risk of causing cost overruns. Therefore, it is necessary to clarify the descriptions of the participants' responsibilities and tasks in the project. This issue arises from the fragmented reality of the traditional contractual relationship between stakeholders.

4.4 Insufficient Information Management

Usually, the project's budget and planning are known as soon as the contract is signed, but in this project, the budget was not clear for the construction team. The client expected the project cost to be lower than the cost of traditional construction but the design team was set to work in an innovative perspective. These circumstances are the probable reasons for higher construction costs. AR acknowledged that innovation leads to extra costs and Eng admitted that they were not aware of a budget limit so the decisions taken were believed to be optimal for the budget.

Moreover, as revealed by the manufacturer, the operational costs related to the factory's requirements can represent between 5 to 50% of the design costs of a project. Given the client's perspective of reducing costs, this was an issue. Eastman et al. (2008) suggested that the accuracy of design information should be considered as one of the main requirements in OSC projects.

5 Discussion

Although OSC may offer great benefits from a perspective of quality and process improvement, in the presented case study, we found an insufficient budget issue which hampered the realization of the project. This issue is due to poor communication and immature construction project procedures. Improving communication efficiency can be achieved by using an information system such as building information modeling (BIM). Because of its centralized information database, BIM allows anyone involved downstream to extract the necessary plans and documents to achieve his task and bring him to the same level of information as all the other stakeholders. BIM improves coordination and collaboration within a project.

The lack of experienced local stakeholders identified by the client can be addressed through government incentives, which could encourage the industry to adopt OSC. As experiences and knowledge are gained, there will be less uncertainty and less risks of cost overruns. These financial incentives could be in the form of subsidies to manufacturers who have an OSC business model or training programs given within the construction industry.

According to the interviewees, cooperative contracts should be used for OSC projects to ensure transparency between stakeholders. Based on a study carried out on a range of prefabrication strategies used in North America, Carbone et al. [20] concluded that a revision of the traditional construction process for a collaborative management process is required to gain higher integration of prefabrication in construction projects. According to the authors of the study, to successfully benefit from off-site construction, collaboration between stakeholders and systematic coordination should be the main objectives. This conclusion is confirmed by the interviewees. Thus, collaborative approaches, such as integrated project delivery (IPD) contracts, would be promising strategies to deploy to help manage OSC projects.

6 Conclusion

This research aimed to investigate the factors that cause higher project costs in prefabricated wood building projects in Québec. In the literature, cost was identified as a major barrier limiting the use of OSC in mid-rise multi-storey buildings. The case study of a mid-rise prefabricated building project shows that information management, project organization and the OSC paradigm are the current challenges faced by the industry. A collaborative environment should be adopted early in the design stage to enhance information gathering. Changes should be made to the contract to consider the new tasks and responsibilities of participants. We recommend that more technology be involved in the information exchange based on BIM, thus enhancing communication and information exchange throughout the processes.

Acknowledgements This study was supported by the *Groupe de recherche en Intégration et Développement Durable* (GRIDD) of École de Technologie Supérieure.

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Management Strategies, Project Teams, and Value Added Using Lean Project Delivery for Sustainable, Reliable, and Effective Construction

P. W. Plugge, H. Dang, and D. Martin

1 Introduction

The process of planning, design, and construction of any major construction project is a complex endeavor among many stakeholders. To ensure a smooth delivery of a project, a formal system should be in place to allow all of the stakeholders to contribute their disciplined related knowledge associated with the job to identify the cost, schedule, quality, and safety parameters that are integrated to manage the risk. On any project regardless of the delivery method, the effort to bring a project within a stated budget, on time, meeting quality standards, and no accidents has shown to create a level of complexity to meet these goals.

It can be argued that construction projects by their nature are complex operations. As Plugge [1] illustrates, many different individuals and factors interact during the construction process. Project complexity is the consideration "of the innumerable individuals involved in the process starting with the owner, builder, the design professional, construction representative, subcontractor, supplier, and the entire professional and non-professional team members working under these responsibilities" ([2], p. 17). Each professional constructor on a project will manage multiple factors related to the econometrics, politics, environment, technology, and the project. Davies [3] argues with respect to complex environments, "there is a very strong need for more and better implementation studies that can identify the particular conditions under which successful implementation and delivery takes place or fails to take place" (p. 13). Key constructs associated with Lean project delivery are centered around econometrics, politics, environment, technology, and specific project factors. The Lean project delivery system has been established as a "culture" centered continuous improvement process to create more value for the customer while identifying

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S. Walbridge et al. (eds.), *Proceedings of the Canadian Society of Civil Engineering Annual Conference 2021*, Lecture Notes in Civil Engineering 247,
https://doi.org/10.1007/978-981-19-0968-9_14

and eliminating waste that allows a team to operate in unison to create project flow (leanconstruction.org). Through the use of experts in many different elements of Lean project delivery, this paper attempts to explain gaps in previous research in how the Lean culture interrelated within management strategies, project teams, and how Lean brings a value added element to project delivery.

2 Review of Literature

2.1 Project Delivery

Project delivery, also known as project delivery method, is "a system for organizing and financing design, construction, operations and maintenance activities that facilitates the delivery of a good or service" ([4], p. 59). Project delivery is broken into several other categories that define the contractual relationship among the parties that are involved in the process to construct a project. These relationships are the basis for the exchange of knowledge, information, evidence, and deliverables to shape the delivery of a project, "typical contractual relationships that brings together a team for the design and construction of a project include the traditional approach, owner-builder, turnkey (design-construct or design-manage professional construction management, and program management (includes program consultant and integrated project team)" ([5], p. 25). The types of project delivery that are commonly available include design-bid-build, design-build, construction management, integrated project delivery, construction management at risk [6]. While there are many project delivery systems available to the owner to organize the stake holders for a proper delivery of a major construction project it is important to engage all of the stakeholders with the project early on to create a good flow of information.

It has been well stated with any delivery method construction projects require several disciplines to coming together to complete a project. As Beck [7] argues there are certain hidden values that can be identified within a delivery process and there are many "discontinuities" as a result of bringing several disciplines together that to be integrated as one entity to complete the end goal creating waste within the delivery of a construction project. Beck [7] also mentions the fact that examples of waste within the construction process are commonly centered around the following examples (p. 32):

- Plans and specifications are insufficiently coordinated and are rarely completed before construction commences.
- Shop drawings and requests for information (RFIs) are used to complete design during construction.
- Change orders are frequently a result of the user's inability to read two-dimensional plans.
- Drawings do not incorporate recent changes in manufactured components.

- Most value engineering evolves into a scope reduction effort and rarely takes into consideration related effects on such things as design.

2.2 Research Related to Lean Project Delivery

Research associated with lean project delivery has been centered around concepts related to management processes, project team characteristics, and the value added. Comparisons have also been made with lean construction and lean manufacturing, while significantly different in the number of products produced, the management techniques to develop a product to final use are similar. A theoretical model from concepts created in lean manufacturing, utilized a case study testing six lean construction techniques to include the last planner, increased visualization, first run studies, huddle meetings, the five S's in Japanese: Seiri, Sieton, Seiso, Seiketsu, and Shitsuke (i.e., sort, set in order, shine, standardize, and sustain), and fail safe for quality on a parking garage. The project team researched individuals that held professional roles as planning team, project manager, subcontractors, foremen, carpenter, and laborers. Interestingly, the findings on using lean management techniques were centered on budget, time, quality, and safety. This research showed how lean project delivery techniques brought the project under budget by three weeks, satisfied subcontractors on their relationship with the general contractor (GC), no injuries occurred, and incident rates were below normal for a similar project [8]. It has been well stated that construction projects carry a certain amount of complexity with the numerous activities and resources available that must be managed.

Planning construction projects as a management process have also been researched related to lean project delivery. Lean project delivery utilizes several different approaches to organize and manage the ebb and flow of a project. A management process frequently utilized in Lean project delivery is through the use of Building Information Modeling (BIM). Studies have shown that architects, engineers, and constructors (AEC) have found the use of BIM to be beneficial within Lean project delivery practices along with other technologies. Examples of these technologies include augmented reality, drones, and advanced building materials that tend to increase the productivity of the project team to distribute information during the design and construction process [9]. Heigermoser et al. [9] studied BIM and the last planner tool for improving project management, they found when combining BIM and Lean construction practices allowed the constructors to minimize waste and creating a collaborative environment while providing efficiencies in information transformation, flow, and value generation for the project stakeholders. In addition to BIM, the process of value streaming is often used to assist with the management process in Lean project delivery. Ko and Chung [10] identified within the lean design process, there is a significant association between Lean and waste during planning and design. They summarized that there is a certain flow identified in the design process for Lean projects starting with preliminary design, basic design, and detailed design. They established the concept that there is an "organizational learning environment within the design flow" ([10], p. 10). A significant finding in this study found that in order to assist the flow, design experience and the expertise of the actual individuals on the project affects the quality outcome of the product through value streaming during the Lean design process.

2.3 Lean Project Delivery

Principles and methodologies associated with Lean production are focused on the ultimate goal of perfection while eliminating waste. This was done through a process of "creating value through efficiency, constructive and collective organization, while using a delicate balance between employee satisfaction through process improvements that create value for a company and the external needs of customers" [11]. Toyota Motor Company has often been cited for creating and implementing the lean methodology and thinking to that ultimately benefits the end user for business and increase profits. It should be noted that Henry Ford created some concepts of Lean with regards to the idea of flow within the manufacturing system. Manufacturing engineers Kiichiro Toyoda, Taiichi Ohno, several others at Toyota studied Ford's processes to solve problems with "continuity in process flow and a variety of product offerings" and ultimately created the Toyota Production System (TPS) [12].

With all project delivery methods there are features that make them unique. The Lean Project Delivery System (LPDS) was first introduced by Glenn Ballard in 2000. Schottle [13] identifies the key characteristics of the LPDS as the following (https://leanconstructionblog.com/What-is-the-lean-project-delivery-system.html):

- The project is structured and managed as a value generating process
- Early involvement of downstream stakeholders to plan and design the project steps through cross functional teams
- Pull techniques are used to manage the information and material flow between stakeholders
- Buffers are used to absorb variabilities in the production system through global optimization

Ballard and Tommelein [14] conducted research within lean project delivery on the last planner system of production control and detailed five (5) different benchmarks for the control process to include master scheduling where the process sets milestones and phase durations and overlaps. Within phase scheduling process of control, the team will specify handoffs and conditions of satisfaction between processes and phases. In the look-ahead planning process the team will identify and remove constraints by breaking down the tasks from processes into operations. Once the tasks and operations are specified, the next step is to make reliable promises through commitment planning on key specific project outcomes. Through this process the last planner will also go through a learning stage to identify countermeasures to keep on task with the project.

2.4 Lean Terminology

There are many key features found in Lean construction that are related to maximizing efficiency through management processes, project teams, and adding value to the process. These key features depending on the project can affect the value of a project by eliminating waste within the management process, depending on the project. All of these key terms related to the Lean project delivery method can be associated with management processes, the organization of the team, or value added. Key terms most commonly found in the literature are included in Table 1. These adopted definitions for this study are from the Lean Construction Institute [15] and were commonly found throughout the literature review process and effectively reflect the Lean project delivery method's features.

3 Methodology

This research associated with Lean Construction utilized a qualitative meta-analysis process to identify the effective strategies that make the Lean Construction project delivery process an attractive option for project owners to deliver their project within the budget and time constraints and meet quality and safety standards specified by industry. As Glass [16] explains, meta-analysis is "the statistical analysis of a large collection of analysis results from individual studies for the purpose of integrating the findings" (p. 3). The methodology for this research used over forty (40) documented articles to identify the integrated concepts associated with the Lean project delivery system and attempt to provide a broader context as to the common construction management practices and strategies related to the Lean project delivery process. The methodology attempted to answer the following research questions:

1. What *management strategies* have been implemented or identified by owners, engineers, and contractors in construction using the Lean project delivery?
2. What are the Lean Project Delivery processes are related to the *project team*?

Table 1 Lean concept items

Economics	Time/schedule	Cost	Quality	Safety
People	Environmental	Last planner	Planning	Waste
Subcontractor	Engineer	Architect	Owner	Relationship
Effective practices	Maximization	Project team	Value added	High value
Low value	Productivity	Sustainability	Planning	Design
Construction process	Social	Activities	Technology	Actual cost
Allowable cost	Buffer	BIM	Pull-planning	Politics
Commitment	Constraint	Flow	Work in progress	Systems
Phases	Mapping	Work plan	Workflow	Consultants

3. What are the *value-added* characteristics associated with the process when the Lean Project Delivery system is utilized?

Qualitative meta-analysis uses an exploratory research process. Routio [17] explains that the researcher starts with a vague idea of the notion of the project and through the exploratory research process, develops a clearer picture of ideas and concepts through the exploratory research process. Cooper and Schindler [18] state that "through exploration researchers develop concepts more clearly, establish priorities, develop operational definitions, and improve the final design" as studies are developed (p. 139). They also argue that "while published data are valuable resource, it is seldom that more than a fraction of the existing knowledge in a field is put into writing" (p. 141). Hence, this research will attempt seek information about Lean construction as it applies to the disciplines of architecture, engineering, and construction management. Creswell [19] states that the primary focus of qualitative research is "an inquiry process of understanding based on distinct methodological traditions of inquiry that explore a social or human problem. The researcher builds a complex, holistic picture, analyzes words, reports detailed views of informants, and conducts the study in a natural setting" (p. 15).

A process to develop data on a group of actual projects is challenging to create due to the proprietary information associated with the projects, owners, contractors, architects, engineers, and consultants related to associated with these projects. Therefore, it becomes necessary to develop a set of data from disciplined inquiry as a "creation that results from the collaboration between the researcher and the subjects of research in developing mid-range theory and generating empirical results that advance the interests or increase the capabilities of an identified community" bridging ideas between academia and practice ([20], p. 12). The qualitative process used to explore concepts associated with the Lean project delivery system included a simple factorial analysis approach to identify common itemized themes between articles and within the suggested article and case study data set. This research approach is grounded theory in the process of "parsimoniously describing data, factor analysis explicitly recognizes that any relationship is limited to a particular area of applicability" representing an area of generalization between and amongst the factors ([21], p. 2). Using a structured scoring system, the word themes were prioritized by the how they much they were related to the three research questions using a Likert scale associated with management processes, project team, and the potential value added associated with the lean project delivery. In other words, the research attempts to expose the wastes and efficiencies related to project management processes, the people skills associated with the project, and value related to the overall process. Each of the research questions were analyzed by how much each article related to the particular research question.

3.1 Limitations

As with any research there are limitations associated with the study. There are several other papers that discuss Lean project delivery, the authors were limited within the literature to use articles that pertained to management strategies, teams, and value associated with Lean project delivery. An elimination process associated with keywords was used to screen articles to narrow down the information to be specific to this study. The study was also limited to articles centered around information gained through United States (U.S.) construction practices related to Lean project delivery. This is a limitation only because the U.S. construction practices can frequently have more flexibility in the services offered.

4 Results

All data was categorized based on three key elements associated with lean project delivery to include management processes, project teams, and value added associated with the lean delivery system. Reviews of the articles allowed the researcher to code the articles based on key terms associated with lean delivery to identify the relationships of management processes, project teams, and the value added with the associated terms. A priority was placed through a manual process to identify the frequency of each of the items shown below to indicate their significance within the articles as they related to lean project delivery. Articles used for this study are refereed peer reviewed scholarly journals which provide a large group of professionals who have studied many of the themes in great detail as data used for analysis. Shown below are items that were used to theoretically code the associations with each of the research questions grouped by their significance with lean project delivery related to management processes, project team characteristics, and value added through the lean project delivery method. Each of the constructs were tested to determine the relationship of each of the grouped items.

The results varied for each category where the means (M) were compared to determine their level of significance within the groups for management processes, project team characteristics, and value added through the lean project delivery process. In order to determine the significance of the variables within the groups studied for management processes, project teams, and value-added statistical means were used with their appropriate variables as identified in Table 2. There was a total of forty-three (43) peer reviewed articles used for this study related to the Lean project delivery system a strong Cronbachs alpha of 0.88 was achieved with each of the Lean categories studied. A factor analysis was performed to confirm the theoretical factors and find communalities to determine which factors would be correlated. Therefore, a principal axis factor analysis with varimax rotation was conducted to assess the underlying structure for forty-three (43) items based the metanalysis of the published Lean articles (the assumption of independent sampling was met. The assumptions of

Table 2 Lean project delivery themes

Management processes	Project team	Value added
Constraints	People	Low/high value
Phases	Commitment	Sustainability
Pull-planning	Architect	Allowable costs
Work-flow	Engineer	Environmental
BIM	Contractor	Quality
Design	Subcontractor	Time/schedule
Construction process	Project team	Cost
Mapping	Consultants	Safety
Effective practices	Relationships	Efficiency
Planning		Social
Buffers		Economics
Activity planning		Maximization
Work plan		Productivity
Relationships		Design
Work in progress		Technology
Management systems		Actual cost
Technology		

normality, linear relationships between pairs of variables, and the variables' being correlated at a moderated level were checked). Three factors were requested, based on the fact that the items were designed to index to three constructs: Management Processes, Project Teams, and Value Added. After rotation, the first factor accounted for 17.8% of the variance, the second factor accounted for 9.8%, and the third factor accounted for 7.4%. Table 3 displays the items and factor loadings for the rotated factors, with loadings less than 0.30 are removed for clarity.

These clustered factors represent the items that show the most communality related to the Lean project delivery system given the research articles and case studies reviewed. The items that show a higher loading greater than 0.40 (>0.40) were used to reduce the total number of items to be analyzed in this study. Items with the higher loadings within their respective theoretical associations were used to be recoded due to consolidate and explain their association with management strategies, project teams, and value added through the Lean project delivery process. Figure 1 shows the items from the exploratory factor analysis process that the researcher used to develop regression models where most of the factors seemed to be numerically grouped together based on their loadings and communalities to the constructs of management strategies project team, and value added. For this study some items were consolidated from clusters found during the exploratory factor analysis.

As these items were recoded, regression models were created to identify strengths of the constructs in the theoretical map were truly linked together and explained by applying numerical values to those items in the exploratory factor analysis. Using the

Table 3 Factor loadings from principal axis factor analysis with varimax rotation for a three-factor solution for lean project delivery items (N = 43)

Item	Factor loading			Communality
	1	**2**	**3**	
Economics			0.499	0.730
People			0.307	0.795
Allowable cost			0.356	0.935
Commitment	0.361		0.453	0.756
Phase	0.697			0.905
Time/schedule	0.536			0.787
Constraint	0.353	−0.588		0.749
Mapping	0.413	0.497		0.784
Cost	0.450	0.480		0.672
Last planner	0.498			0.868
Architect/engineer	0.514		−0.567	0.875
Contractor	0.464		0.363	0.861
Project team	0.498	0.332	−0.445	0.842
Sustainability		0.416		0.898
Activities	0.312	−0.467		0.896
BIM	0.491			0.820
Flow	0.454			0.856
Work plan	0.591			0.753
Quality	0.434			0.904
Owner	0.323			0.812
Work in progress	0.453	0.525		0.779
Work flow	0.391	0.459		0.826
Safety	0.481		0.304	0.847
Waste	0.559		0.356	0.801
Relationship	0.390		−0.333	0.789
High value	0.559			0.703
Design	0.759			0.862
Construction process	0.438			0.814
Actual cost	0.354			0.858
System	0.632			0.785
Pull planning	0.565			0.658
Work in progress	0.453			0.779
Eigenvalues	7.65	4.21	3.19	
% of variance	17.8	9.80	7.42	

Note Loading <0.30 are omitted. Not all items are shown

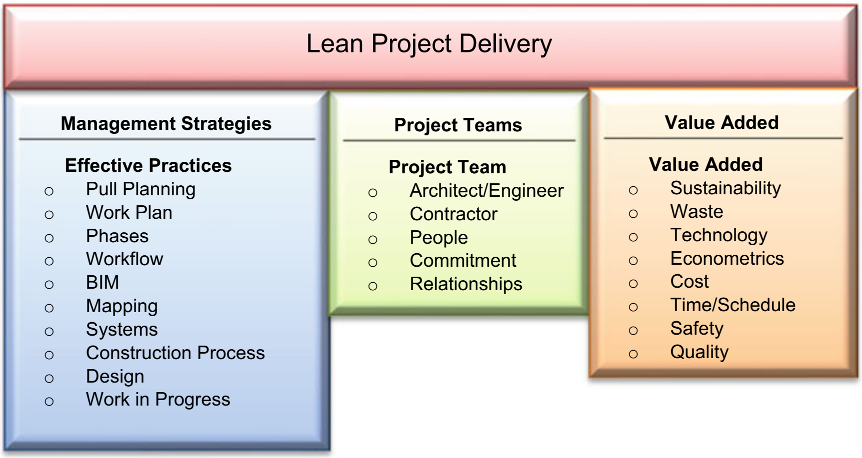

Fig. 1 Exploratory factor analysis item reduction model

regression model helped to answer the questions to common construction management practices associated with Lean construction as to the management practices, project team, and value added as they are related to the Lean project delivery system.

A regression analysis was used to determine the influences on the three constructs of management strategies, project teams, and value added as they relate to Lean project delivery and with the final goal of answering the research questions. For each construct a One-Way Analysis of Variance (ANOVA) and correlations were used to determine the significance each construct being analyzed (Tables 4, 5, 6, 7, 8 and 9).

Based on the data that was analyzed for this meta-analysis the three tables show the significance of each of the constructs being tested. What the articles are trying to explain are the important constructs associated with Lean project delivery. As can be seen from the ANOVA tables, the items shown for management practices show little significant correlation when, $F(10,29) = 0.552$, $p = .839$. For value added, there seems to be a very low significant correlation when, $F(7,32) = 0.518$, $p = .883$. Out of all three constructs, the most significant construct from the article and case study information is the construct of project teams as indicated by, $F(7,32) = 6.774$, $p < .001$.

Table 4 One-way analysis of variance summary for ***Management Practices***

Source	SS	Df	MS	F	Sig
Between groups	11.170	10	1.117	0.552	0.839
Within groups	58.73	29	2.025		
Total	69.90	39			

$p = .839$

Table 5 Interitem correlation matrix for ***Management Practices***

Item	Effective practices	Pull planning	System	Const. process	BIM	Workflow	Mapping	Phase	Work plan	Work in progress	Design
Effective practices	1.00										
Pull planning	0.24	1.00									
System	0.31	0.41	1.00								
Const. process	0.25	0.35	0.54	1.00							
BIM	0.10	0.46	0.37	0.43	1.00						
Workflow	0.19	0.18	0.20	−0.15	−02	1.00					
Mapping	0.06	−0.03	0.24	0.08	0.18	0.06	1.00				
Phase	0.12	0.31	0.30	0.32	0.56	0.33	0.37	1.00			
Work plan	0.28	0.24	0.41	0.31	0.16	0.44	0.13	0.26	1.00		
Work in progress	0.15	0.39	0.29	−0.06	0.09	0.66	−0.05	0.27	0.40	1.00	
Design	0.18	0.41	0.59	0.45	0.54	0.11	0.35	0.59	0.35	0.17	1.00

Table 6 One-way analysis of variance summary for ***Project Teams***

Source	SS	Df	MS	F	Sig
Between groups	66.50	7	9.50	6.774	0.000
Within groups	44.88	32	1.40		
Total	11.38	39			

$p < .000$

Tables 4, 6, and 8 show the interitem correlations for each of the constructs for management practices, project teams, and value added. These tables provide the possible relationships for the items within the constructs related to Lean project delivery. For management practices and value added a review of these tables shows there are few high value correlations within each of these constructs.

5 Discussion and Conclusion

This meta-analysis provided an opportunity to use peer reviewed research and case studies as a way to research the communalities related to management strategies, project teams, and value-added strategies on Lean project delivery. This research did provide some interesting correlations with respect to the data, through the initial exploratory factor analysis the communalities seemed to similar results to previous research performed on Lean project delivery. It should be noted that during the exploratory analysis process the researchers did consider the idea of crossing some of the items to a different construct category due to the uniqueness of the item. An example of this would include the concept of “relationships” which could be closely correlated to the items of the last planner within management strategies, people within project teams, and value in value added constructs. Exchanging some of the items to different constructs could improve the data associated within each of the constructs.

This research sheds some light on the potential concepts where Lean project delivery could benefit the construction process. The methodology of this research quasi-statistically identified previous disciplined research and case studies on Lean project delivery to explain the important constructs of management practices, project teams, and value added with Lean project delivery. While the items within management practices and value added seemed to indicate they were least correlated, there was a higher significant correlation associated with the project teams who use Lean project delivery. This appears to identify the fact that Lean project delivery exposes the importance of the professional relationships and commitments between and with the architect, engineer, constructor, subcontractors, and the people who work on the project. Lean project delivery brings constructors together from multiple different disciplines to create a workflow that establishes a process to complete a final end

Table 7 Interitem correlation matrix for ***Project Teams***

Item	Project team	People	Architect	Owner	Contractor	Commitment	Relationships	Engineer
Project team	1.00							
People	−0.03	1.00						
Architect	0.69	−0.10	1.00					
Owner	0.27	−0.18	0.35	1.00				
Contractor	0.62	0.03	0.49	0.17	1.00			
Commitment	−0.10	0.11	0.07	0.06	−0.23	1.00		
Relationship	0.36	0.00	0.37	0.18	0.25	0.11	1.00	
Engineer	0.26	−0.04	0.44	0.30	0.20	0.07	0.23	1.00

Table 8 One-way analysis of variance summary for ***Value Added***

Source	SS	Df	MS	F	Sig
Between groups	12.683	8	1.585	0.518	0.833
Within groups	94.817	31	3.059		
Total	107.500	39			

$p = .833$

product, in many cases a unique project that an be rarely replicated. While the materials and construction methods may differ from project to project, what can be replicated are the management processes deployed by the project teams with an overall goal to bring value to the project. In summary, the significance of this research leads to the fact that the project team is solely responsible for the management practices and the overall value added to the Lean project delivery system. Statistically, data analyzed from the refereed articles and case studies seem to support this notion.

Future research would find other project delivery methods and study their relationships with management practices, project teams, and value added with respect to the delivery method. Related to Lean, other studies would look further into the weaker correlated constructs in this study to find the key components related to Lean project delivery that make the management practices and value added an important feature that would encourage owners to use Lean project delivery as a method to procure their project. Lean project delivery has been cited to be an efficient delivery method, studies which bring the key features used in Lean project delivery on heavy civil projects related to pull planning, value streaming, and BIM modeling would be of particular interest since many heavy civil projects use the design-bid-build project delivery method and currently use many of the management practices associated with Lean project delivery to determine how close of a relationship there may exist with management practices within different types of project delivery systems. Integrated project delivery is sometimes known by some authors as Lean project delivery, future research would delve further into the extreme differences and similarities that exist between these two delivery methods to further define them as separate delivery methods or how similar they really are in structure. There seems to be evidence that exists to show the intercorrelations on how management practices, project teams, and value added that may exist between several different project delivery systems, not just Lean project delivery.

Table 9 Interitem correlation matrix for ***Value Added***

Item	Value added	Waste	Sustainability	Technology	Economics	Environmental	Time/schedule	Quality	Safety
Value added	1.00								
Waste	−0.07	1.00							
Sustainability	0.06	−0.04	1.00						
Technology	−0.16	−0.22	−0.00	1.00					
Economics	0.09	0.04	0.03	0.05	1.00				
Environmental	0.07	0.24	0.53	−0.06	0.18	1.00			
Time/schedule	−0.18	0.38	−0.17	0.05	0.12	0.15	1.00		
Quality	−0.14	−0.36	−0.18	0.14	0.00	0.24	0.39	1.00	
Safety	0.11	0.31	0.03	0.00	0.10	0.27	0.24	0.30	1.00

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Evaluating Risk Indices for Execution Plans of Construction Activities: Energy Sources Approach

Ayesha Siddika and Ming Lu

1 Introduction

Construction work is inherently dangerous. Sharp objects, heavy loads, working at heights, and emphasis on production all give rise to risks for accidents. Good planning practice along with the implementation of a comprehensive safety program is necessary for delivering a safe project. A recent study has proposed a matrix of shaping factors accounting for how accidents arise from a failure in the coordination between workplace, work team, equipment and material [1]. Numerous studies have shown that employee involvement in a safety program is essential to safety performances. Modern planning and scheduling methods include advancements in cost analysis, resource assessments, and the incorporation of safety in project planning. Identifying and assessing the hazards and risks in construction operations is an essential step in safety management [2–4]. Hazard assessment attempts to anticipate and prevent potential problems from manifesting themselves at the worksite. It is often far less expensive to prevent problems at the construction planning stage than to modify the work site later so as to eliminate or mitigate a hazard. Risk index is generally calculated by assessing the likelihood and severity of a risk entered subjectively by an experienced safety officer. Conventional project risk management approaches in the project feasibility stage emphasize managing business risks and often ignoring operational risks. However, there are instances of project failures because of operational risks in terms of technical complexities, contractors'

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S. Walbridge et al. (eds.), *Proceedings of the Canadian Society of Civil Engineering Annual Conference 2021*, Lecture Notes in Civil Engineering 247,
https://doi.org/10.1007/978-981-19-0968-9_15

and suppliers' incapability, government red tape etc. Previous studies have analyzed accident causation in construction and most followed statistical approaches based on historical accident data. Nonetheless, such data are often scant, ill-structured, and unsuitable for computing the risk index at activity levels. To address this issue and reduce the bias of experts' judgment, a more systematic guideline needs to be formulated to allow for consistency and reduce subjectivity in evaluating the risk index. Furthermore, before developing the guideline, a question needs to be assessed: why findings from previous studies remain to be challenging to be implemented by safety experts in practice. This paper proposes a detailed method for safety risk assessment on activities of a project with regards to the ten major types of energy release categorized by the American Society of Safety Professionals,they are: Mechanical, Biological, Temperature, Chemical, Pressure, Electrical, Radiation, Sound, Gravity and Motion. Finally, a demonstration case is developed to check the applicability of the proposed method in practice.

2 Literature Review

Construction Job Safety Analysis (CJSA) is a structured method for hazard analysis and assessment of construction activities. It has been developed within the framework of research towards a lean approach to safety management in construction, which requires the ability to predict fluctuating safety risk levels in support of safety conscious planning and pulling safety management efforts to the places and times where they are most effective. The method involves identifying potential loss-of-control events in detailed stages of the activities commonly performed in construction and assessing the probability of occurrence for each event identified. The CJSA process comprises three major steps; namely: hazard identification, probability assessment and assessment of severity. Fung et al. [5] developed a Risk Assessment Model (RAM) to assist safety management by examining current safety problems in construction and investigating various types of risks on different work trades.

Sadeghi and Lu [6] developed a model that factored accident risks in the context of the classic time–cost trade-off problem definition. It resulted in an optimum solution for the time–cost-safety trade-off (TCST) problem. It is noteworthy that a risk index is developed to add safety assessment to the decision-making process based on the critical path method. The TCST problem was formulated as a nonlinear programming model, which was further demonstrated and validated in a case study with a few hypothetical what-if scenarios. This study revealed that the imposition of risk index would markedly affect the resulting TCST problem optimum solution.

Aminbakhsh et al. [7] proposed a novel framework based on the theory of cost of safety (COS) model and the analytic hierarchy process (AHP) in efforts to facilitate safety risk assessment. This framework presents a robust method for prioritizing safety risks in construction projects, aimed to create a reasonable budget and set realistic goals without compromising safety. According to the COS model, there is a theoretical equilibrium point at which the total costs of prevention and detection are equal to injuries' total costs, reflecting the optimum investment. The COS model also supports the presumption that a certain safety risk level is considered acceptable to maintain an organization's financial stability. The proposed framework first divided the decision problem into a hierarchy of more easily comprehensible sub-problems, each of which was analyzed independently. The elements of the hierarchy were identified in accordance with construction safety risk problems. Once the hierarchy was built, experts assigned a numerical scale to each pair of alternatives by making a pairwise comparison with respect to impact on the element placed in the higher level in the hierarchy. A priority index for each expert's judgment was determined by converting evaluations of risks into numerical values. Then, based on the processed weights of the AHP, numerical values were compared and risk items were prioritized.

Tian et al. [8] proposed the fuzzy analytic hierarchy process (AHP) method to evaluate work safety in hot and humid environments. It was difficult for crisp numbers to measure behavioral and qualitative factors, such as safety training and personal protection. The human assessment of qualitative attributes was subjective and thus imprecise. Therefore, conventional AHP was inadequate to capture decision-maker's requirements explicitly [9]. In order to model this kind of uncertainty in human preference and capture human reasoning, the principle of fuzzy logic was introduced. Trapezoidal fuzzy numbers were utilized to handle inherent uncertainty and imprecision of the data involved in the decision process. With the proposed methodology, a decision group was first established. A safety evaluation framework containing three factors (work, environment, and workers) and ten sub-factors were established. The fuzzy weights of the factors and sub-factors were calculated based on pairwise comparisons. Then the fuzzy evaluation vectors of the sub-factors and factors were calculated according to the initial evaluation data. Therefore, the comprehensive safety index, safety grade and early warning grade were determined using an example to demonstrate the practicability and effectiveness of this method.

3 Risk Factors

Based on the review of previous studies, it is found that the input information used for different methods of analysis is either sourced from a qualitative survey of the industry experts or from historical data-based analysis. The major drawback of this procedure is that the extracted information may vary from person to person as the factors considered can be different. A generic categorization of risk factors is desired to increase consistency and reduce subjectivity in eliciting information on safety risks. According to the American Society of Safety Professionals principle, energy sources for injuries and losses in the construction industry are classified into ten significant categories [10]. Related risk factors in connection with these energy releases can be analyzed for safety risk assessment. A checklist is given considering these factors to address all the possible risks (Table 1).

Table 1 Checklist to assess safety risks on construction activity by energy sources for injuries and loss

Serial No.	Type of factors	Related risk factors	Description
1	Mechanical	Rotating equipment	It must be checked whether there are any guard and devices to prevent access to dangerous areas
		Compressed springs	
		Drive belts	
		Conveyors	
		Motors	
2	Motion	Vehicle speed, collisions and sudden stops	A wide variety of mechanical motions and actions are hazardous to workers. So, risk needs to be checked on mechanical motions and actions
		Vessel or equipment movement	
		Flowing water	
		Wind action	
		Body positioning	
		Lifting	
		Straining	
		Bending	
3	Gravity	Falling object	It needs to be checked whether there is any measure to control gravitational hazards by understanding the magnitude of forces
		Collapsing roof	
		Body tripping	
		Falling from a height	
4	Sound	Impact noise	As there is no effective treatment for hearing loss, needs for hearing protection and the scope of noise should be checked to avoid exposure to loud continuous noise; workers wearing hearing protection or not; reducing work time around loud noises
		Vibration	
		High-pressure relief	
		Equipment noise	
5	Radiation	Lighting issues	The sources of energy emitted from radioactive elements and naturally occurring radioactive materials need to be identified for addressing risks
		Welding arc	
		X-rays	
		Solar-rays	
		Naturally occurring radioactive materials	
		Non-ionizing sources	
6	Electrical	Power lines	How vulnerable the site is subject to the presence and the flow of electric charge should be checked
		Transformers	
		Static charges	
		Drive belts	
		Conveyors	
		Motors	

(continued)

Table 1 (continued)

Serial No.	Type of factors	Related risk factors	Description
7	Pressure	Pressure piping	Whether there are any regular monitoring and maintenance in place to identify leaks from high pressure hydraulic lines, hoses, tanks, etc. needs to be checked
		Compressed cylinders	
		Control lines	
		Vessels	
		Tanks	
		Hoses	
		Pneumatic and hydraulic equipment	
8	Chemical	Flammable vapors	Chemical hazardous materials should be handled carefully. So, the potential of hazardous chemical reactions should have been checked to assess this risk
		Reactive hazardous materials	
		Carcinogens or other toxic compounds	
		Combustibles	
		Corrosives	
		Pyrophoric materials	
		Inert gas	
		Welding fumes	
		Dusts	
9	Temperature	Open flame and ignition sources	The temperature of the worksite needs to be checked in order to assess associated risks
		Hot or cold surfaces	
		Liquids or gases	
		Friction	
		Bad environmental condition	
		Steam	
		Extreme or changing weather condition	
10	Biological	Bacteria	Any risks that come from the biosphere needs to be checked: whether the employees working around other people who may have diseases or around animals and insects or working around potentially hazardous pathogens or sewers etc. or any hazardous materials in the working environment that need to be cleaned up regularly
		Animals	
		Viruses	
		Insects	
		Bloodborne pathogens	
		Contaminated water	
		Any other risks stemming from the biosphere-like people, plants or animals	

4 Risk Index Evaluation Methodology

The evaluation of hazards and risks can be conducted by systematically implementing risk assessment, inspection, and field level surveys aligned with the proposed checklist (Table 1). While collecting data, it needs to be confirmed whether the project plan considers the associated tasks or scopes of work relevant to those risk factors identified above. If the answer is 'Yes', the magnitude of the factors should be assessed. The following procedure can be followed to guide the calculation of the risk index value on a project activity.

4.1 Calculation of Risk Index for Individual Factors

To calculate the average risk index for each risk factor mentioned in Table 1, the probability and severity for the occurrence of the factor need to be fixed at first based on the particular project situation. The following rating systems (Tables 2 and 3) to assign risk point for each particular factor can be utilized. Equation 1 is used to consolidate the risk index value for each category of risk factors.

Risk Index for each individual factor,

$$RI_i = \sum_{i=1}^{n} Pi * Si \tag{1}$$

Table 2 Severity index scale to assign risk point for each factor (*Source* ACS 11)

Value	Qualitative value	Remarks
10	Catastrophic	Multiple permanent injuries or irreversible health effects to the workers An event that impacts the construction operation and causes substantial delays The incident leading to death
8	Major	Major injury leading to long-term incapacity or disability Requiring time off work for >14 days
6	Moderate	Moderate injury requiring professional intervention Requiring time off work for 4–14 days Agency reportable incident An event which impacts on a small number of workers
4	Minor	Minor injury or illness requiring minor intervention Expected delay <3 days
2	Negligible	Minimal injury requiring no/minimal intervention or treatment No delays Minor property damage
0	No risk	No injuries, damage or delays

Table 3 Probability scale to assess the risk of each factor [12]

Probability score	Description	Probability	Remarks
1.00	Certainty	1	Certain to occur
0.95–0.99	High	> 0.95 < 1	Extremely sure to occur
0.85–0.95	High	> 0.85 <= 0.95	Almost sure to occur
0.75–0.85	High	> 0.75 <= 0.85	Very likely to occur
0.65–0.75	High	> 0.65 <= 0.75	Likely to occur
0.55–0.65	Medium	> 0.55 <= 0.65	Somewhat greater than an even chance
0.45–0.55	Medium	> 0.45 <= 0.55	An even chance to occur
0.35–0.45	Medium	> 0.35 <= 0.45	Somewhat less than an even chance
0.25–0.35	Low	> 0.25 <= 0.35	Not very likely to occur
0.15–0.25	Low	> 0.15 <= 0.25	Not likely to occur
0.00–0.15	Low	> 0.00 <= 0.15	Almost sure not to occur

Here,

RI_i Risk Index for each type of energy release.
P_i Probability of each factor.
S_i Severity of each individual factor.

4.2 Calculation of Risk Index for Each Type of Energy Release

The risk index calculation for each individual energy source is derived through the following mathematical Eq. 2. Herein, the risk index value for each type falls on the range of 0–10.

$$\text{Risk Index for each type of energy release} = \frac{\sum_{i=1}^{10} RIi}{n} \quad (2)$$

Here,

RI_i Risk Index for each individual factor.
n Total number of factors in each type of energy release sources.

4.3 Calculation of Risk Index for Each Activity

The risk index is calculated by adding up all the values for each risk factor associated with the activity. The final risk index value ranges from 0 to 100. Equation 3 has

Table 4 Interpretation of risk index value (*Source* NIST [13])

Qualitative values	Quantitative values	Description
Very high	96–100	Very high risk means that a threat event could be expected to have multiple severe or catastrophic adverse effects on construction operations, assets, individuals, other resources
High	80–95	A threat event could be expected to have a severe or catastrophic adverse effect on the operation of that specific activity
Moderate	21–79	A threat event could be expected to have a serious adverse effect on the operation of that specific activity
Low	5–20	A threat event could be expected to have a limited adverse effect on the operation of that specific activity
Very low	0–4	A threat event could be expected to have a negligible adverse effect on the operation of that specific activity

been used to calculate the final risk index for a specific activity. Interpretation of the final risk index value can be illustrated by Table 4.

$$\text{Risk Index for Individual Activity} = \sum[\text{Risk Index of Each Type of Energy release}] \quad (3)$$

5 Case Study

5.1 Project Description

For concept proof, a case study is described for checking the applicability of the model in the construction field. The case pertains to the painting operation of a bridge construction project. With numerous complex activities associated with a bridge construction project, painting operation was chosen to illustrate the risk index calculation. With environmental, health and safety related concern, painting a bridge structure was an expensive operation. Coating failures are mostly caused by either deficient surface preparation or coating application. Painting operations generate dust, solvent fumes, and noise. So, environmental constraints governing the project are crucial, along with proper and safe disposal of abrasive material applicable to existing paint removal according to the applicable laws and regulations [14].

Table 5 Risk factors associated with painting operation

Type	Risk factor associated	Description
Mechanical	Presence of rotating equipment	There was no guard and devices to prevent access to danger areas
Motion	Vessel or equipment movement	An abrupt movement of trucks and cranes; high wind; flowing water under bridge
	Flowing water	
	Wind action	
Gravity	Falling object	No guardrail systems with toe boards and warning lines or install control line systems to protect workers near the edges of floors and roofs
Electrical	Power lines	New energized (hot) electrical circuits without all power shut off and attached grounds
Temperature	Steam	Near a hot spring, hot steam presence. Weather condition is unpredictable on the site
	Extreme or changing weather condition	
Chemical	Welding fumes and spills of chemicals	Hazards associated with chemicals which can cause chemical burns, respiratory problems, fires and explosions

To calculate the risk index value for this specific activity, the associated risk factors were identified first and then the proposed methodology was applied to estimate the final index value (Table 5).

5.2 Risk Index Evaluation

After identifying all associated risk factors, the probability and severity of each factor were assigned by those who were responsible for recognizing hazards and taking effective measures to prevent injuries, and cultivate a safety culture at the construction site (e.g. managers, supervisors, safety coordinators, construction foreman, and the site engineers). Following the risk index evaluation methodology, the risk index value is calculated, given in Table 6.

5.3 Discussion

The calculated total risk index value for the painting operation on the bridge construction project is at 24.8, which indicates the moderately low value of risks. It is interpreted as a threat event that could have a serious adverse effect on the operation of

Table 6 Risk index calculation

Type	Risk factor	Severity		Probability value		Risk index for each type of energy release
Mechanical	Presence of rotating equipment	Major	8	Very likely to occur	0.85	6.8
Motion	Flowing water	Moderate	6	Somewhat greater than an even chance	0.65	3.45
	Wind action	Minor	4	Likely to occur	0.75	
Gravity	Falling object	Moderate	6	Not very likely to occur	0.35	2.1
Electrical	Power lines	Minor	4	An even chance to occur	0.55	2.2
Temperature	Steam	Catastrophic	10	Almost sure to occur	0.95	9.75
	Extreme or changing weather condition	Catastrophic	10	Certain to occur	1	
Chemical	Welding fumes and spills of chemicals	Negligible	2	Not likely to occur	0.25	0.5

that specific activity (according to Table 4 of the Risk Index Evaluation Methodology section).

6 Conclusion

The construction industry continues to make inroads regarding achieving safe, reliable, and sustainable operations in the field. Safety remains a major concern in the construction industry. At the project planning and scheduling stage, there is a practical need to identify the hazards and assess the associated risks. Hazard identification and risk assessment are carried out by identifying undesirable events that could lead to a hazard, analyzing inherent risks, and estimating its extent, magnitude, and the likelihood of harmful effects. Numerous risk assessment techniques contribute significantly toward improvements on the safety of complex operations and activities in construction. Still, there is room for enhancement in terms of quantifying the risk index value, which can be used to identify the severity of any associated risks activity of the construction project. The case study in this research is limited to one specific activity (the painting operation of a bridge construction project). Therefore, considering a complete project and assessing associated risk factors of project activities could give rise to the risk index value of the overall project.

The energy sources-based approach provides a new structured framework model to address complex occupational health and safety (OHS) related risk evaluation, which serves as a potential new standard to classify, identify, and assess OHS risks on construction projects. However, in the proposed index evaluation method, each particular energy source's risk assessment on a project still utilizes the conventional technique that can be subjective and dependent on individual experts. Formal brainstorming sessions would be effective in reconciling discrepancies resulting from subjective assessment. The ensuing research will address such limitations by providing more specific and quantitative guidelines for risk index assessment in particular application domains. For instance, in tunneling, certain energy sources would be quantitatively analyzed based on physical configurations and equipment used on site. Respective energy sources will also be elaborated in the project specific context and further analyzed, instead of only counting on domain experts' experiences.

Acknowledgements The presented research is partially funded by Occupational Health and Safety (OHS) Futures Research Funding Program (Grant #095245033) of the Government of Alberta, Canada.

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Effective Safety Protocols and Project Productivity Impacts for Construction Companies in Washington State During the COVID-19 Pandemic

J. Serne and H. Dang

1 Introduction

The novel coronavirus disease 2019 (COVID-19) is a contagious respiratory illness caused by a new coronavirus (i.e., SARS-CoV-2) infection [1]. Found Wuhan City in China in December 2019, the COVID-19 quickly spread all over the world. The United States reported the first confirmed case in Seattle, Washington, on January 22, 2020. Many other states quickly confirmed more and more cases. The United States became the center of the COVID-19 pandemic with 20% of the accumulative confirmed case in and after May 2020. Figure 1 illustrates the confirmed new cases every day and the seven-day average new cases between January 22, 2020, and February 20, 2021 [2]. As of February 20, 2021, the number of accumulated deaths was 504,971. The highest was 306,524 on January 8, 2021, with a seven-day average of 261,321 confirmed new cases. The symptoms include but are not limited to fever or chills, cough, shortness of breath or difficulty breathing, fatigue, muscle or body aches, headache, the new loss of taste or smell, sore throat, congestion or runny nose, nausea or vomiting, and diarrhea. The Centers for Disease Control and Prevention [1] suggests seeking emergency medical attention for warning signs such as trouble breathing, persistent pain or pressure in the chest, new confusion, inability to wake or stay awake, and bluish lips or face [1].

The COVID-19 pandemic certainly affected every industry in the United States, particularly the construction industry. In addition to the emergency plan to respond to the pandemic, many construction projects were either temporarily on held or permanently completed. All 50 States required all non-essential enterprises to be

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S. Walbridge et al. (eds.), *Proceedings of the Canadian Society of Civil Engineering Annual Conference 2021*, Lecture Notes in Civil Engineering 247,
https://doi.org/10.1007/978-981-19-0968-9_16

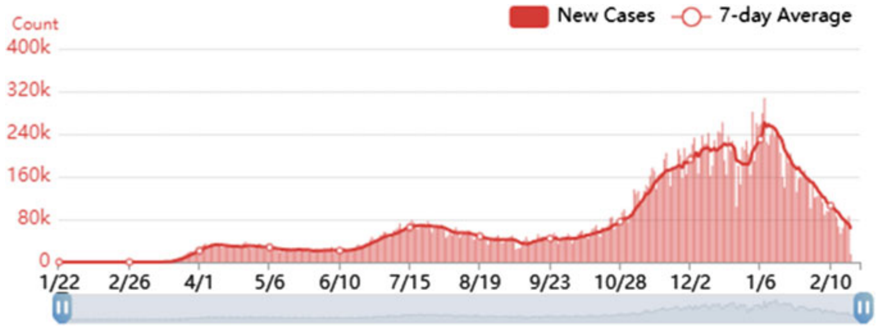

Fig. 1 COVID-19 new cases and seven-day averages in the United States as of February 20, 2021

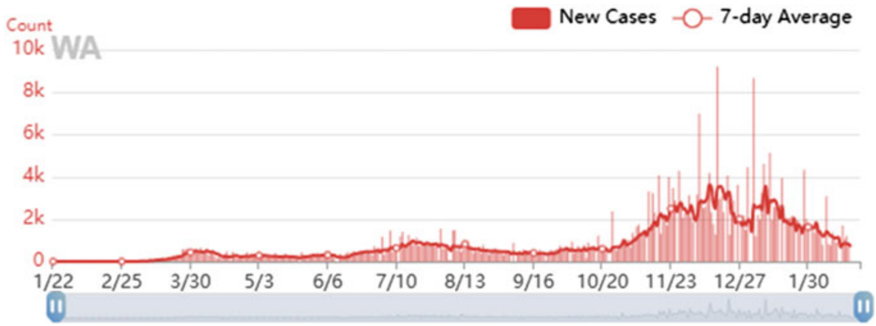

Fig. 2 COVID-19 new cases and seven-day averages in Washington state as of February 20, 2021

closed to the public. Figure 2 shows confirmed new cases every day and the seven-day average new cases between January 22, 2020, and February 20, 2021 [2].

After these mandated shutdowns, Washington construction companies could work on only a handful of essential construction projects. Additionally, even some essential jobs closed because they could not comply with the Center for Disease Control (CDC) newly recommended guidelines. The recommended CDC guidelines for keeping you safe from the COVID-19 pandemic are expected to be followed: (1) cleaning your hands (hand sanitizer is acceptable if >60% alcohol), (2) avoiding close contact with others (required six-foot radius), (3) covering your nose and mouth (especially when sneezing and coughing), and (4) cleaning and disinfecting all surfaces.

2 Literature Review

COVID-19 continues to be a rapidly emerging and developing public health emergency, so there is very little literature on the impact of COVID-19 on the construction industry. This lack of scholarship was particularly prevalent when this study began in March 2020, which marked the beginning of the US pandemic of COVID-19. At this time, the first response to the pandemic in Washington State was to effectively close all business activities, including construction, except that specific projects were considered essential. A small amount of existing literature suggests that the suspension of construction work was a common action taken by many governments both in the United States and internationally during this time [3–5].

In Washington State, those construction projects which were deemed essential and therefore continued to operate were suddenly tasked with the difficult charge of maintaining the health and safety of their workers and preventing the spread of the novel virus among their crews. Concerns about the ability to maintain safety forced some job sites, which could have remained open as essential construction projects, to cease operations simply because they were unable to comply with the guidelines of the Center for Disease Control (CDC). The guidelines were the only guidance available at the time for controlling the hazards of COVID-19. However, shortly after the shutdown, the Washington State Department of Labor & Industries (L&I) issued a bulletin entitled *Dealing with COVID-19 (coronavirus) in Construction.* This bulletin from the state agency tasked with oversight for worker health and safety included guidance for keeping construction personnel healthy on essential work sites while the rest of construction projects were still at a halt due to the shutdown. This guidance which covered four major topics, "Ideas for Social Distancing on Construction Sites," "Employer Actions," "Employee Actions," and "Respirator Conservation," was very similar to the policies and guidelines formulated by the World Health Organization (WHO). Literature suggests these policies and guidelines be implemented in the construction industry in other parts of the world [5]. However, other nations, such as South Africa, have implemented a rule requiring construction sites to follow the WHO guidelines [5]. This was not the case with L&I's guidance, as it did not constitute a formal regulatory process. In fact, the bulletin even stated that "L&I does not require all employers to make their employees aware of the risks associated with [COVID-19]" [6]. Thus, although this bulletin provided the industry with much-needed advice to maintain the health and safety of workers, it was not enforceable and merely constituted an attempt by L&I to maintain the safety of essential workers while the Governor's office was developing a more in-depth plan.

The first topic, 'Ideas for Social Distancing on Construction Sites,' provided suggestions to ensure that social distancing was followed during essential gatherings and meetings that must occur on construction sites, such as mandatory training sessions and toolbox talks. When this bulletin was distributed, the gatherings were restricted to 10 or fewer people with a recommendation for a 6-foot distance between individuals. To this end, the guidance for gatherings on construction sites recommended that all meetings be split into multiple sessions to allow for minimizing groups to 10 people or fewer. The guidance also suggested that meetings should be held outdoors whenever possible, regardless of size. Working with subcontractors to change schedules so that crews could have staggered work shifts was also recommended, as were other efforts to minimize the number of workers on a single job site. Also, guidance was provided for the use of equipment that could place people in proximity, such as lifts and elevators. The guidance recommended that the use of such equipment should be avoided and that only one person should use such equipment at one time if elimination is not possible. The guidance also suggested the selection of a "Social Distance Monitor similar to a safety monitor" [6]. The purpose of the "Social Distancing Monitor" was to enforce and remind workers of the recommendations set forth by L&I. It was suggested that employees choose a person who can lead by example in a positive way, such as a foreman or other supervisor.

The second set of recommendations in the L&I Bulletin were related to "Employer Actions." The first recommendation in this section suggested that employers should ensure that workers are fully educated about the COVID-19 virus, such as handwashing and social distancing, and kept up-to-date on the rapidly changing CDC guidelines. This section also included recommendations on handwashing, including training, handwashing station installation and maintenance, and frequent cleaning of common touch-point areas. Handwashing recommendations were followed by guidance on health check procedures for employees, including temperature checks. The third category of recommendations in *Dealing with COVID-19 (coronavirus) in Construction* covered "Employee Actions." These recommendations consisted of suggestions to encourage employees to apply the workplace standards to their personal lives. Topics included proper coughing and sneezing etiquette, handwashing before touching the face, proper hand cleaning, avoiding sharing items such as food, phones, tools, and PPE, and staying at home when sick.

"Respirator Conservation" was the last area of recommendations in the bulletin and served as an attempt to set guidelines for respirator use that would reserve certain types of respiratory protective equipment for use in the healthcare setting by encouraging the construction industry to forgo their use. These recommendations were based on the Center for Disease Control's (CDC) guidance, which eschewed the wearing of facemasks for healthy people and was appropriate for a nationwide shortage of masks for healthcare workers existed. L&I also recommended against the use of masks unless it was a required piece of the PPE for the given work. Additionally, they suggested postponing non-essential construction work requiring types of respiratory protection that were in short supply because of the lack of masks.

Approximately one month after L&I posted their bulletin, the Governor of Washington State, Jay Inslee, instituted the first actual construction legislation related to COVID-19 on April 23, 2020. In contrast to L&I's bulletin, Governor Jay Inslee's *Phase 1 Construction Restart COVID-19 Job Site Requirements* did establish regulatory mandates. Enforcement of Phase 1 was to begin on May 5th, 2020 and at that time it was predicted that the state would not be expected to move to a less restrictive Phase 2 until late May or early June of 2020. This gave contractors in Washington State only 12 days to fulfill the requirements of this new mandate on their construction sites. Inslee's requirements began with the statement, "Any existing construction projects complying with the points below may resume only those work activities that do not require workers to be closer than six-feet together" [7]. In cases where the workers were unable to maintain this 6-foot distance during the regular operation of the work, the work was considered high risk and was not authorized. Additionally, Governor Inslee's plan required all contractors to create, develop, and post a COVID-19 exposure control, mitigation, and recovery plan at each job site [7].

Failure to post a plan would result in the closure of the job site and sanctions by the state and local authorities. Phase 1 included seven main categories of requirements to be followed to legally reopen the construction site, including "COVID-19 Site Supervisor," "COVID-19 Safety Training," "Social Distancing," "Personal Protective Equipment (PPE)—Employer Provided," "Sanitation and Cleanliness," "Employee Health/Symptoms" and "Job Site Visitors." Sites were only legally allowed to reopen if they were able to meet all seven categories of requirements.

The first requirement of the Governor's mandate was that any reopening of construction sites should have a "COVID-19 Site Supervisor." This site supervisor was required to be present at all times and at all job sites, except for single-family home construction jobs with fewer than six people on site. The second requirement to comply with the reopening of construction sites was the establishment of a specific safety training program for COVID-19 to ensure that all employees understood the requirements of the new rule. This mandate explicitly required that this COVID-19 specific safety training take place on the first day that all contractors returned to work. These training meetings be continued weekly with six-foot distances required between the participants. These ongoing meetings aimed to ensure that employees were fully aware of all protective measures and kept up-to-date on rapid changes to the recommendations and rules.

The next requirements were related to "Social Distancing." The CDC had begun to recommend a six-foot separation as a minimum for social distancing at the time of the rulemaking. These recommendations also called for extra precautions during deliveries to job sites, such as minimal cross-contact between paperwork and pens. The rule also required that "choke points" and "high-risk areas" be identified and pointed out to employees and that staff breaks and lunches be taken in shifts to minimize the number of people in gathering areas. The fourth set of rules applied to 'Personal Protective Equipment (PPE)—Employer Provided.' These PPE requirements were not intended to replace possible stricter PPE requirements for a specific construction task but mandated specific PPE to be worn for tasks that do not typically require PPE, such as latex gloves and masks and face shields. The lack of masks, gloves, and other PPE required at this time caused some contractors to shut down job sites due to the inability to provide the required PPE.

"Sanitation and Cleanliness" was the fifth category of requirements under *Phase 1 Construction Restart COVID-19 Job Site Requirements.* All job sites were required to have an abundance of handwashing stations, whether permanent or portable, per WAC 296-155-140 2(a)–(f). It was further mandated that the soap supplies should be checked and restocked frequently. Alcohol-based hand sanitizers with more than 60% ethanol or 70% isopropanol could also be used but were not considered as a replacement for regular water-based handwashing facilities. Contractors were also required to post reminders around the job site to prompt employees to clean their hands using the proper washing technique. In addition to the washing stations, contractors also had to have disinfecting supplies available to sanitize frequently handled items such as equipment, tools, door handles, and railings.

The second and final requirement of the Phase 1 ruling covered "Employee Health/Symptoms" and required employers to allow employees to work from home whenever possible and take steps to encourage employees to stay at home if they have any kind of illness. In addition, employees were required to report ill family members to their supervisor, even if they did not experience any symptoms. Those with ill household members were required to self-quarantine before returning to the workplace. All employees coming from outside Washington State to work on a project were required to self-quarantine for 14 days before reporting for duty. In addition, temperature checks, preferably using a non-contact thermometer, were required before employees could enter their job site. The temperatures of employees had to be recorded and it was mandated that employees with a measured body temperature of 100.04 °F were to be sent home. If an employee on a job site happened to contract COVID-19, it was required that the contractor sanitize all things that person may have come in contact with. The last requirement of Governor Inslee's Phase 1 plan for construction covered "Job Site Visitors." This Directive required all and every visitor to sign in and sign out of the workplace daily. Contractors were required to keep official records of all visitors' names, phone numbers, and email addresses for at least four weeks.

At the time this study commenced, most job sites that had been allowed to reopen had only been open for a week. With only one week of experience with the new mandates to draw from, the feasibility of implementing these requirements or their efficacy in helping to prevent the spread of COVID-19 was somewhat unclear. In addition, the COVID-19 situation continued to evolve rapidly, and contractors were only given a 12-day window to make the necessary changes to reopen all jobs. At the time, it was difficult to determine what the impact of these new rules would have on the industry or how many contractors would have been able to comply with them to reopen their work sites. Besides, the general perception of the industry towards the Phase 1 mandates was unknown. Therefore, this research was undertaken to determine how the contractors were dealing with the situation and potentially discover new ways of successfully navigating these unprecedented conditions.

3 Research Design

The authors used a sequential explanatory mixed-method approach to investigate effective safety protocols and project productivity impacts for construction companies in the state of Washington immersed in the COVID-19 pandemic. The initial quantitative study collected survey responses in May 2020. The following qualitative study conducted interviews in February 2021.

3.1 Quantitative Surveys

The authors have developed a survey to collect data from construction contractors. The survey consisted of eight questions related to the impact of the COVID-19 pandemic and effective safety protocols. The survey was distributed to 25 construction companies in Washington State through the Washington Network of Associated General Contractors in May 2020. Each company representative was asked to forward the survey to the safety managers in the distribution. Of the 25 construction companies, 16 responded to the survey at a response rate of 64%. Twelve commercial contractors and four heavy civil contractors were present. Besides, the authors collected data from the Washington State Department of Transportation staff (WSDOT).

3.2 Qualitative Interviews

In February 2021, the authors collected three qualitative interviews from construction safety managers overseeing major heavy civil construction projects and smaller residential and commercial construction projects in Washington State. The interviews included four open-ended issues related to the impact of the Government shutdown on construction activities and projects, as well as new public health regulations and safety protocols, including voluntary and innovative measures that have been identified as being most effective in alleviating the negative impact and risk of COVID-19.

4 Results and Discussion

Synthesized and validated results of surveys and interviews concluded the impact of the COVID-19 pandemic, effective safety protocols, and construction project productivity.

4.1 The Impact of COVID-19 Pandemic

The COVID-19 pandemic has had a significant impact on construction projects in Washington State due to increased safety requirements. Figure 3 shows the heat map of active construction projects based on survey responses in May 2020 and the number of confirmed cases for approximately 140 construction projects between March and December 2020. The most active construction projects were in the counties of Pierce and King. Some counties had several active construction projects. Others may not have an active construction project. There was a total of 30 confirmed COVID-19 cases, six in Pierce, five in King and four in Kittitas County.

Survey participants were asked if they did not meet, met, or if they exceeded the Phase 1 Protocol standards for the reopening of construction activities mandated by Governor Inslee. Participants were asked to briefly state why their company

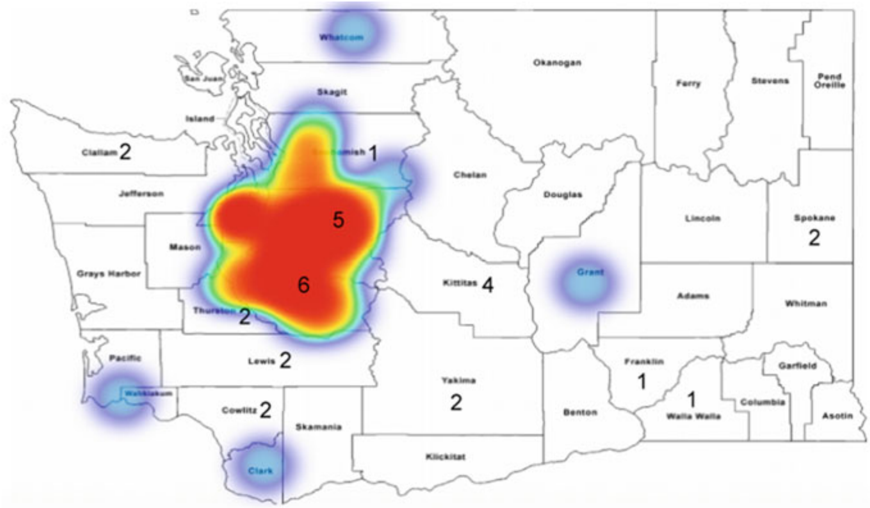

Fig. 3 Heat map of active construction projects based on survey responses and numbers of confirmed cases on construction projects from WSDOT

complied with or exceeded Phase 1 compliance. All the participants who said that their company met the requirements of Phase 1 summarized that they closely monitored all the Governor's announcements and followed all the rules set out therein. The 31% who responded, exceeding the standards, all mentioned that they had essential jobs that were up and running while everything else was shut down. Therefore, these companies were able to identify additional safety protocols that their company considered necessary, whether it was an extra distance between workers or an extra step in the sanitation of the workplace. Figure 4 illustrates the perspectives of the safety manager on the adequacy of the standard to ensure that construction workers in the field are safe and healthy. 72% of survey participants believe that the requirements are to keep the workforce safe, but 28% believe that more can be done. Some would think that it should be 100% one way or the other since the participants are in the same field of work and all have the same goal of keeping people safe. There are many different views on COVID-19, which could be the reason why not 100% of safety managers are on one side.

Statistics indicate that the mandated protections did keep construction workers safe from Covid 19. Table 1 compares WSDOT construction project COVID-19 Cases between March and December 2020 with the number of infections and rates within Washington State overall. There were only 30 reported positive COVID-19 tests amongst the 140 active construction projects and approximately 5,000 personnel, including both contractors and WSDOT workers.

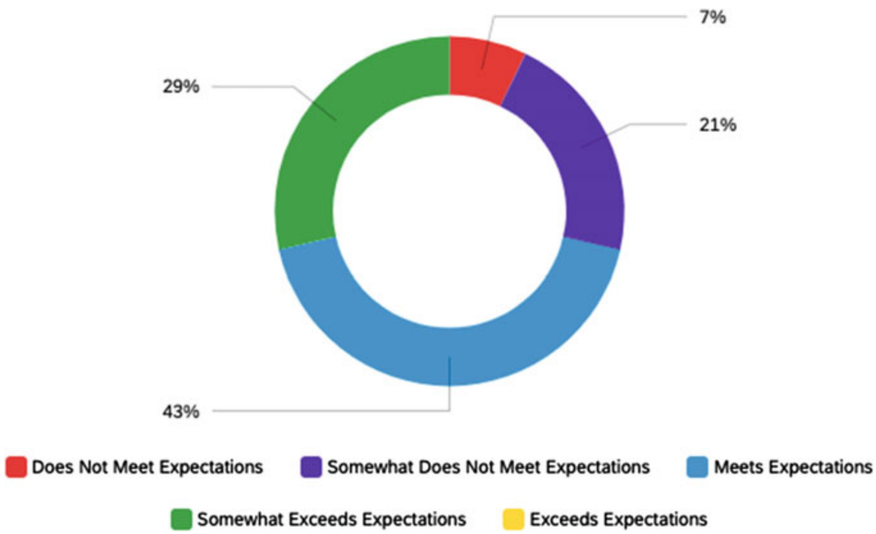

Fig. 4 Safety manager's perspectives on the adequacy of the standard to keep construction field workers safe and healthy

Table 1 A comparison confirmed COVID-19 cases and infection rate between WSDOT construction projects and the overall state

Description	WSDOT construction projects	The overall state
Confirmed COVID-19 cases	30	246,376
Approximate number of people	5,000	7,200,000
Infected people per thousand	6	34.2
Inflation rate	0.006	0.0342

4.2 *Effective Safety Protocols*

The initial outbreak and ongoing surges of the novel coronavirus (COVID-19) required the construction industry to adopt rigorous and innovative safety protocols. Initially, many projects were put on hold, and only essential projects could continue after proper safety measures were put in place. The authors collected documents and interviewed construction safety managers in Washington regarding the safety protocols and practices they implemented in construction projects during the early days of the pandemic and the impact of these practices on the workforce and productivity. The data analyzed revealed several effective safety protocols and innovative strategies in response to the pandemic.

As discussed in the literature review, the Phase 1 rules of Governor Jay Inslee required companies to implement safety measures in seven main categories. These additional protocols mandated by Phase 1 were legally required to be implemented at every active construction site. Survey participants were asked how much focus their company had placed on each category. These results are shown in Figure 5 and reflect how companies handled the new requirements at the onset of the pandemic by indicating how much the company's focus is on implementing the mandated requirements to reopen its work sites. Most companies reported that they had placed an average or above average amount of focus in each category, although one company did not select a target for all seven categories, which was clearly an anomaly. The results show that the implementation of these new safety requirements has added a lot of workload to the day-to-day activities of the company. Implementation of these mandates required significant investment in time, money, and materials before work could be restarted and revenue from projects could be restored. This stretched the resources of the companies and, due to the additional resources needed to meet all the new sanitation, PPE, and social distance requirements, 81% of the companies surveyed reported that they could not open all the jobs that had previously been active in COVID-19. The remaining 19% who stated that they were not affected indicated that this was because all their active operations were considered to be essential at the start of the pandemic and therefore did not require a shutdown.

The 81% of companies that reported not yet operating 100% had similarities. Although they were slowly opening up jobs, there were significant challenges that prevented them from meeting the phase mandates at a level that would allow for full reopening. One participant stated that they had begun a "roll start" in that,

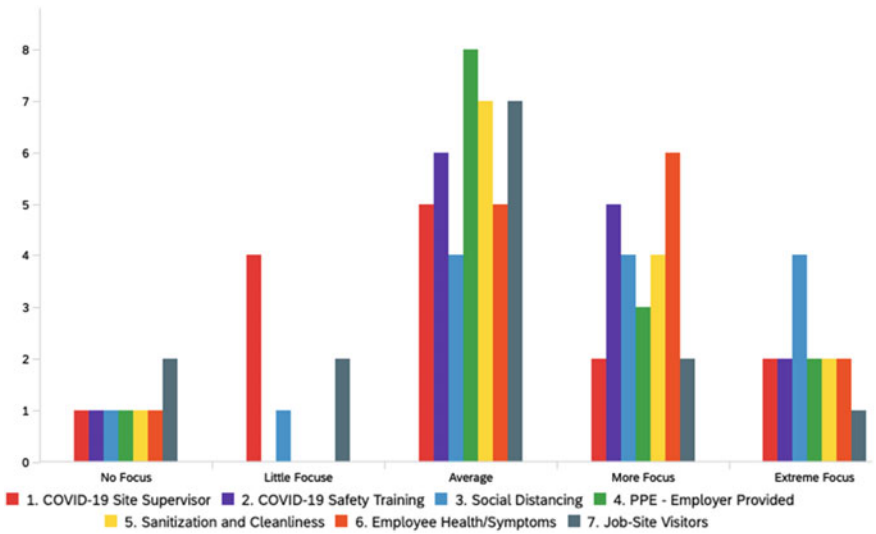

Fig. 5 Survey responses on safety focus of Governor Inslee's seven categories for reopening

although all their job sites had been reopened to a large extent, there were limiting factors such as the need for PPE and other equipment or materials needed to meet phase 1 requirements successfully. Another company reported that some projects had been asked to remain closed because they did not want to cover the cost of unproductive or slower production. Some companies reported that they remained fully functional. However, these companies represented entities with only essential worksites that had never been fully shut down. Overall, the survey indicated that the Phase 1 requirements had an impact on the construction industry and that companies appeared to be investing a lot of resources in implementing safety protocols. In addition, many companies indicated that they needed more time to implement the new requirements at all their job sites, and those companies that were able to continue to work on key jobs in compliance with the L&I newsletter were able to reopen earlier than those that had experienced a complete shutdown.

Several themes on which safety protocols were effective and some innovative approaches to meeting these protocols emerged from the interviews. In response to Governor Inslee's Phase 1 rule, all interviewees mentioned challenges related to the need to develop complex and integrated safety plans. The timeframe for completion of these plans ranged from three weeks to three months. The fastest turnaround times were for companies that had avoided a complete shutdown and had already implemented L&I's guidance. One participant noted that their own plan had been drawn up based on WHO guidelines even before L&I's guidance bulletin had been circulated due to considerable foresight from their organization, but most participants reported starting the process shortly after L&I's guidance had been disseminated but prior to phase 1 requirements. Another commonly mentioned challenge was the difficulty of maintaining these plans in compliance during a rapidly evolving situation with frequent rule changes. All participants pointed out that the amount of uncertainty from day to day was difficult to manage and tax.

All interviewees indicated that the greatest challenge to meet Phase 1 or L&I requirements at the onset of the pandemic was to secure supplies for sanitization and PPE. One construction company supervisor reported that the company had taken the novel approach of working with local distilleries to produce its own hand sanitizer. This product was stored and packaged in a barn owned by the safety manager and other staff while awaiting full reopening. In addition, the company produced disinfectants and paper towels from the dairy industry instead of their regular supply chain, an unusual yet effective approach.

Another common challenge among participants was the implementation of social distance protocols. Construction work often involves tasks that do not allow workers to keep a distance of six feet. One company established additional levels of respiratory protection beyond face masks for workers engaged in this work. Another company reported that, to reduce the number of people they contacted, they built a QR code website so that workers could sign up using their phones rather than using a pen, minimizing the potential to spread contamination. Similarly, the implementation of a rule restricting workers from traveling around work sites in the same vehicle has been implemented by one company to maintain social distance. A novel approach to the monitoring of social distances has been reported by a company that has established the use of proximity detection devices to warn workers if they are located within six feet of another worker on site. The use of these devices has also been useful in increasing awareness of the need for additional training or redesign of work tasks to ensure social distance and contact tracing.

All the safety professionals interviewed also mentioned the importance of making it easier for workers to comply with new rules by means of measures such as ensuring that work vehicles are properly stocked with the PPE, the daily COVID-19 specific safety meetings, and, in one case, the designation of the COVID-19 specific safety liaison, which was responsible for educating and helping the workforce to meet the requirements. They also reported some unexpected challenges, including worker resistance to safety protocols for personal and political reasons. Buying in from subcontractors was more challenging than expected, especially when it came to off-site behaviors. In one case, it was reported that a few key personnel left the company rather than complying with the protocols they felt were unfounded and an infringement of their personal freedoms.

Overall, participants felt that, although the implementation of new safety protocols was challenging in the face of uncertainty and during a rapidly evolving health crisis, they had great success in maintaining safety at their workplaces through careful planning and implementation of both the required and innovative safety procedures and processes. They all reported no major outbreaks or work stoppages due to COVID-19, with one participant reporting only one case on their job site during the pandemic to date.

4.3 Construction Project Productivity

The COVID-19 pandemic affected the productivity of the construction project at the workplace and in the office. The implementation of effective safety protocols has resulted in a reduction in the productivity of the construction project and an increase in hours for each task due to the handling of COVID-19.

The creation of new safety mitigations and procedures required a significant time investment that diverted workers from their regular duties and caused projects to take longer than usual to complete. Routine work that relied on safety oversight and permitting processes, such as hot work, lifts, and confined space work, had to be delayed as security resources were concerned with handling the new COVID-19 requirements.

Interview participants also reported experiencing productivity issues related to the need to recruit new staff after the start-up of projects and increased turnover. Many workers, including independent contractors and sub-contractors, were sent home at the beginning of the pandemic as construction sites closed and brought back after construction could resume. All participants said that they had some increased hiring needs after work had resumed due to the refusal of some former workers to return to their former jobs after work had been resumed. These new subcontractors and workers had to be hired quickly to bring the staff back to the required level. These new hires have increased the need for remedial training of new staff, in addition to the new training requirements set out in the Phase 1 safety requirements. Participants suggested a variety of reasons why former employees refused to return to their previous positions, including concerns about contracting the virus, encouraging government stimulus, and increasing unemployment to stay at home, and refusing to comply with the new safety guidelines. In addition to the impact on productivity caused by delays due to additional training needs, one participant found that the workers their company was able to recruit during that time were less fit for duty, experienced, and skilled than those who had previously worked on their site. These less capable workers caused further productivity problems due to reduced performance and contributed to an increase in the turnover of the workforce.

5 Conclusions and Limitations

Due to the unprecedented situation of the COVID-19 pandemic, there was very little research and literature on the event. It was challenging to find a reliable source of information in the media, despite the massive amount of discussion surrounding COVID-19. The literature reviewed was the most up-to-date and reliable source available at the time. The survey was conducted at the height of the outbreak and at the beginning of Phase 1. Phase 1 contractors were only allowed to open a week or two before the survey was sent out, so there was a lot of confusion at the time. After the phase plan of Governor Inslee was completed and the contractors had time to settle in this chaos, more analysis was needed. Another curious element is the potential for new safety measures to introduce new hazards. Therefore, to reduce overall safety. It will be useful to examine whether some of the safety measures put in place to prevent the spread of COVID-19 contribute to other problems. For example, the fogging of eye protections due to wearing masks and the inability to detect heat stroke due to face coverings are two possible scenarios where new safety protocols may inadvertently reduce safety.

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Lean Adoption Barriers for Trade Contractors

E. Asadian, R. Leicht, and J. Messner

1 Introduction

The term lean was first used by the research team working on the International Motor Vehicle Program at MIT. It is a Western interpretation of the Japanese production philosophy applied in the car manufacturing industry [17]. This paradigm was initially recognized as a strategic means to better production outcomes, such as improved efficiency, quality, and productivity [15], but soon gained its place outside of the manufacturing industry as a performance improvement method [19]. Efforts to encourage the application of lean theory in the construction industry have been growing worldwide.

The earliest consideration of using lean production ideas within construction is attributed to Lauri Koskela when he devised the transformation-flow-value generation (TFV) model of production [12]. While traditional thinking of construction was only focusing on conversion activities, ignoring flow and value considerations, the TFV model reflected construction as a combination of conversion and flow processes. This perspective helps to both identify and remove waste, such as inventory, motion, and over-production. Subsequently, the five principles of lean were established by Womack and Jones in 1996 as Value, Value Stream, Flow, Pull, and Perfection [26].

Previous studies have shown several benefits from applying lean principles in construction, including improved productivity, increased predictability, better quality, higher client satisfaction, reduced cost, shortened schedules, minimized waste, and improved safety [4, 12, 14, 21]. Despite the many benefits that have been observed from applying lean, there seem to be several barriers limiting the broader

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S. Walbridge et al. (eds.), *Proceedings of the Canadian Society of Civil Engineering Annual Conference 2021*, Lecture Notes in Civil Engineering 247,
https://doi.org/10.1007/978-981-19-0968-9_17

lean adoption and implementation [2, 21]. According to Khaba and Bhar [11], organizations need to identify and overcome these mitigating barriers that constrain firms' greater success.

Although these barriers have been well studied for prime or first tier contractor's, sometimes referred to as the general contractor, the recognition of obstacles to the lean adoption specific to trade contractors is not well documented. The construction sector cannot take full advantage of applying lean unless all stakeholders actively engage in the implementation process. It is in line with the findings of the study conducted by Portioli-Staudacher and Tantardini [18] that excluding involvement of frontline employees by management can cause problems in implementing lean in service companies. Hence, this literature survey seeks to identify and organize trade contractors' possible barriers to successful lean implementation. By establishing the framework for these barriers, trade partners will be better positioned to implement lean by focusing on the key obstacles.

2 Methodology and Literature Review Process

To compile and assess the potential barriers to the adoption of lean by trade contractors, a literature analysis was performed to identify previous studies that captured and evaluated such barriers. The two primary resources used were the databases of papers from the Lean Construction Journal, published by Lean Construction Institute (LCI), and the International Group for Lean Constructions (IGLC) conference proceedings. In addition to a systematic review of these papers, the works cited in the reviewed articles from other journals were also studied, such as the American Society of Civil Engineers (ASCE) Construction Engineering and Management Journal. To choose the relevant papers, articles that discussed lean implementation issues and barriers to lean adoption in the construction realm were selected. Of the dozens of papers reviewed, seven articles had defined the main barriers to adopting lean and will serve as the remaining sections' focus. In total, 29 barriers were extracted from the content analysis of these studies.

To analyze the cited barriers, several passes were made to compare, group, and organize the barriers. First, the full list of these barriers was reviewed, with rankings included if the papers performed a ranking analysis as part of the research. The list was then analyzed to identify the frequency of barriers used in the studies, along with their relative ranks. Following the frequency and ranking analysis, the barriers were reviewed again to determine relevance specific to trade contractors' considerations. Ultimately, the review's final step was to look at the organization of barriers that emerged from the previous literature as a basis for clustering them.

3 Lean Implementation Barriers: A Review

Despite the numerous benefits gained from lean implementation, all organizations cannot successfully implement lean construction. As Jadhav et al. [19] claimed, companies have several reported problems and issues regarding the failure to enforce lean philosophy. Likewise, as Nordin et al. [16] expressed, implementing lean thinking is not an easy task for an organization. Instead, there is tremendous resistance to the implementation process, similar to any other changes. Therefore, these barriers need to be identified and addressed to provide the platform through which the organizational and individual change readiness may be achieved [19].

In this respect, several studies have been carried out worldwide to identify the barriers to implementing lean. Some of these studies focused on obstacles that prevent the implementation of lean [1, 14, 17], while others concentrated on barriers that exist during the execution of lean practices [2, 3, 10]. These barriers could affect the application process of lean and hinder the project performance if not properly managed [13].

In a recent study, Shang and Peng [24] conducted a large-scale survey of Chinese building professionals to empirically address the question of "what barriers would hinder the implementation of lean practices in the construction industry in China." The survey participants were asked to express their level of agreement with the 22 barriers listed. A 5-point Likert scale from "one being insignificant to five being highly significant" was used to investigate whether the given barriers were thought to inhibit the implementation of lean practices. The result of their findings revealed that the three biggest obstacles to the implementation of lean practices include "the lack of long-term philosophy," "the absence of a lean culture in the organizations," and "the use of multi-layer subcontracting." They also applied factor analysis to identify six underlying categories hindering the successful implementation of lean, namely, people and partner, managerial and organizational, lack of support, culture and philosophy, government, and procurement issues. Ultimately, some recommendations to mitigate these barriers were suggested.

Similarly, Sarhan and Fox [21] identified and assessed the possible barriers to implementing lean construction in the United Kingdom (UK). Based on the statistical analysis of data gained from a questionnaire survey, ten barriers were identified. These ten barriers are fragmentation and subcontracting, procurement and contracts, lack of adequate lean awareness and understanding, culture and human attitudinal issue, time and commercial pressure, financial issues, lack of top management commitment, design/construction dichotomy, educational issues, and lack of the use of process-based performance measurement systems (PMSs.) Further analysis of the results revealed that there was a strong level of agreement amongst all participants that the "lack of adequate lean understanding" is the biggest barrier to the implementation of lean practices, followed by "lack of top management commitment," and "cultural and human attitudinal issues," [21]. These two studies' findings are relatively close regarding the top barriers, suggesting the notion that the barriers may be similar across countries and cultures.

In another study conducted by Ayarkwa et al. [4], potential barriers to the successful implementation of lean construction in the Ghanaian building industry were identified and prioritized by adopting a structured questionnaire survey of 400 construction practitioners. This study also proposed measures to overcome these barriers. Based on the mean scores of factors identified, the five most substantial obstacles to the implementation of lean construction in Ghana are ranked as fragmented nature of the industry, extensive use of subcontractors, lack of long-term relationship with suppliers, delays in decision making, and waste accepted as inevitable, in that order. Like the previous surveys, fragmentation and subcontracting were also demonstrated as significant barriers to implementing lean practices [4].

Senior and Rodríguez [23] examined the perceived importance, easiness to overcome, and criticality of 29 barriers to productivity improvement in the Dominican Republic. In this study, obstacles were grouped into three main categories, environment driven, top management driven, and field-management driven. In 2011, Brady et al. specifically concentrated on Last Planner System (LPS) implementation projects. They tried to identify barriers and determine whether or not factors contributing to lean projects were present in the LPS implementation projects. They stated that poor communication and transparency, minimum involvement of construction workers, inadequate training, lack of role definition, information not adequately used, lack of time for implementing improvements, and eventually, lack of integration in the production chain are barriers to the last planner system implementation [7].

In addition to these studies conducted specifically on the barriers, Christensen et al. [8] concentrated on the motives of implementing lean principles. In this study, project team members' different motivations to work with lean construction and continual improvement were explored. The findings from a survey on lean implementation and the motivation to work with lean via questionnaires revealed that the ability to improve the work processes and contribute to better quality, savings, and time reductions are among the motives that encourage project participants to implement lean principles. While "not sufficient knowledge," "not sufficient time," and "not expecting from the team members" are some demotivators for lean adoption. They also argued that by setting explicit expectations, the senior managers could be motivated to support and resource lean adoption [8].

4 Analysis of Rankings

The full list of barriers identified across all of the studies is summarized in Table 1. These studies mainly target adopting lean principles within the main contractor's firm-level, and tangible examples of investigations on how trade contractors can be encouraged are scarce. Few research studies have been done specifically focusing on trade contractors. The few that focused on trade contractors did not explicitly investigate how the contractors can be motivated to adopt lean principles at a project level. Despite this shortcoming, the construction industry can benefit from applying

Table 1 Summary of lean implementation barriers, ranking, and frequency

Barriers	Author	Maturana et al.	Denise Brady	J. Ayarkwa	Bolivar Senior	Sarhan & Fox	Shang & Peng	Christensen et al.	Frequency of use	Relative Ranking
	Country	Chile	UK	Ghana	Dominican Republic	UK	China	UK		
	Year	2007	2011	2011	2012	2013	2014	2019		
	Journal	Lean Con. Jour.	IGLC	Journal of Const.	IGLC	The Built & Human Environ.	Journal of Tech. Man.	Lean Con. Jour.		
Lack of proper planning and control		0.5	0.4	1	0.4	0.75		1	6	0.675
Lack of teamwork				0.8	1	1			3	0.933
Poor project management		0.5		0.6			0.65		3	0.583
Lack of high manager support						0.35	0.60		2	0.475
Lack of technical capabilities				0.2		0.25			2	0.225
Lack of financial resources		0.5		0		0.45			3	0.316
Poor communication between parties		0.5	1	0.4		1			4	0.725
Minimum involvement of construction workers		0.5	0.75						2	0.625
Inadequate training		0.5	0.4			0.15	0.50		4	0.387
Lack of requiring team member to adopt lean								0.75	1	0.75
Lack of integration of production chain		0.5	0			0.85			3	0.45
Quality of materials					0.75				1	0.75
Complete designs					0	0.85	0.875		3	0.575
Lack of time		0.5				0.50		0.4	3	0.466
Lack of long-term philosophy						0.65	1		2	0.825
Absence of the Lean culture in the organization						0.65	0.95		2	0.80
Insufficient knowledge of Lean						0.75	0.80	0	3	0.516
Multi-layer subcontracting						1	0.75		2	0.875
High turnover of the workforce							0.55		1	0.55
Resistance to change						0.65	0.45		2	0.55
Employee tolerance of untidy workspace							0.40		1	0.4
Inadequate delivery performance							0.35		1	0.35
Hierarchies in organizational structures							0.30		1	0.3
Less personal empowerment							0.25		1	0.25
Avoid making decisions and taking responsibilities							0.20		1	0.2
Using relationships to conceal mistakes							0.15		1	0.15
Stringent requirements and approvals							0.10		1	0.1
Lack of support from the government							0		1	0
Lack of customer-focused measurement						0			1	0

lean methods and principles by trade contractors. Hence, in the following section, the analysis of listed barriers was performed to identify their importance as a first step in the path to trade contractors broadly deploying lean methods. Subsequently, the relevance of these barriers to trade partners was investigated.

In Table 1, across the top is the list of research studies, with the intersections identifying which barriers each included, as well as a fuzzy ranking based on how they were ranked in that study. The furthest right columns aggregate the frequency of each barrier, in addition to the weighted ranking based on the fuzzy scale and the number of studies that used it. It is noteworthy to mention that although these barriers are framed in the context of general contractor firms, they still provide a baseline to investigate the implementation of the lean principles by trade contractors.

In some of these studies, the authors also proposed the ranking for demonstrating the level of importance of these barriers, which are also identified in Table 1. To highlight the barriers' overall importance, the fuzzy scale was created from 0 to 1, with 1 being the highest rank for the barrier and 0 demonstrates the lowest level in the noted survey. For studies that did not consider any priority for the factors, all of the identified barriers are shown with a value of 0.5 since no priority level was assigned to them in the original papers.

Subsequently, relative rankings' mean value was then calculated to show the relative importance of the barriers to lean construction's successful implementation. Since the numbers of surveyed barriers were different in the previous studies, the highest number of obstacles was chosen as the range of possible ranking values. In this context, the 22 obstacles recognized by Shang and Penge have dictated the range. Hence, the relative ranking of each of these barriers was calculated within the fuzzy scale. Other studies were then converted to this scale so that the mean value of rankings could be calculated. As can be seen in Table 1, the mean values of four barriers, namely: "lack of teamwork," "multi-layer subcontracting," "lack of long-term philosophy," and "absence of the lean culture in the organization," earned the highest values, respectively. These barriers, considered the significant barriers to the successful implementation of lean, are highlighted in blue.

5 Findings and Results

In total, 29 barriers were identified relative to implementing lean practices within the construction industry. Among these barriers, 17 show up in two or more of the publications. The "lack of planning and control" is the most frequently used obstacle in implementing lean principles mentioned in almost all of these studies, followed by "poor communication between parties" and "inadequate training" as the next most frequent factors. These three items, identified by gray color in Table 1, appear to be of central concern to the building professionals and need to be addressed.

As can be concluded from Table 1, there is no linear association between the frequency of use and relative ranking parameters. In other words, "lack of proper planning and control" was recognized as the barrier with the highest frequency in almost all the previous surveys. Still, it is not among the five 'highest' ranked in terms of the significant barriers shown in Table 1.

While the lack of long-term philosophy and multi-layer subcontracting are identified as significant barriers, they are not frequently cited in the previous studies. It can be argued that since lean construction requires substantial shifts in thinking and behavior [25], proper planning and controls are needed for the transition to the new approach of production and serving customers [21]. However, there might be some other factors affecting the implementation of lean with a higher level of perceived impact.

The effect of having a long-term philosophy and multi-layer subcontracting on the success of lean implementation has been well documented in previous studies. As Sarhan and Fox [21] and Shang and Penge [24] claimed, these two barriers are among the most significant preventing the successful adoption of lean. The effect of teamwork on lean implementation success has also been well investigated in several previous studies [1, 5, 6].

Following the frequency and ranking analysis, the barriers were reviewed again regarding their relevance to the trade contractor's considerations. In this respect, three categories were proposed, barriers specific to trade contractors, barriers inclusive of any firms in construction, and barriers that were external to construction firms. Barriers that are out of trade contractors' control, such as "stringent requirements and approvals" and "lack of support from the government," are assigned to the "excluded trade contractors" group. It is evident that having support from the authorities is valuable [19]. However, this factor cannot be addressed within the trade contractor firms—likewise, the project's approval process and requirements. A second category, inclusive of any construction firms, has a broader range as it targets any parties involved in construction activities. These barriers are mainly related to organizations in general within construction and cannot be limited to the trade contractor's adoption. Barriers linked to project management or associated with organizational structures and cultures are located in this category. Lastly, barriers related to procurement, operations, workforce, or other construction aspects that are inclusive and specific to contractors that procure, fabricate, and install some system or component on construction sites were noted within the third category. If the barrier was relevant to the self-perform activities of general contractors, it was listed within the specific to Trade Contractor category. The summary of this grouping can be seen in Fig. 1.

Several studies sought to group or cluster the barriers. Through the literature review process, some did this to identify common or root cause barriers rather than detailed indicators [21], while others used statistical clustering methods to identify trends in the responses and ratings [24]. Both approaches provide different insights into the links and shared considerations in the adoption of lean. The resulting groupings are defined and compared to identify the constructs related to the adoption of lean that can more broadly inform the needed investigation for trade contractors.

In the next step, the previous clustering of these barriers was taken into consideration to assess them more systematically in the context of trade contractor adoption.

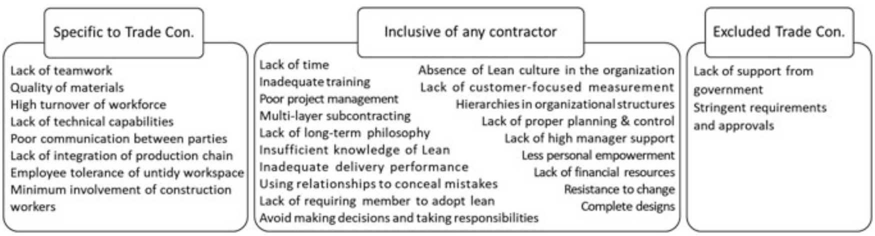

Fig. 1 Relevance of barriers to trade contractors

To do so, various clustering and groupings proposed by some of the earlier authors were studied. Among all, three clusters provided by Ayarkwa et al. [4], Sarhan and Fox [21], and Shan and Peng (2014) were selected as benchmarks due to their relative comprehensiveness. Although there are some similarities among the proposed categories, there is no direct association among them, and the sub-groupings of barriers differed, even when the topics of the groupings were similar. It is evident that some prominent factors, such as managerial aspects, were mentioned by all of these studies, however, few categories were listed only in one of them. Moreover, there are some meaningful overlaps between these groupings, which induced some inconsistencies and limitations in their clustering. For example, Sarhan and Fox [21] recognized two main factors: “fragmentation and subcontracting” and “procurement and contracts,” as different categories. However, the authors believe they both reflect various aspects of “project delivery methods.” In other words, multi-layer subcontracting is an inevitable result of procurement and contract type. Similarly, a complete design, which is considered as a procurement and contract barrier, can also relate to the design and construction dichotomy. In the same way, they separated “insufficient knowledge of lean” from “educational issues.”

Likewise, Shan and Peng (2014) separated managerial and organizational barriers from a lack of support barriers. However, in the latter, they include the lack of managers’ support as one of the significant obstacles in implementing lean practices. These are some examples that need to be addressed so a consistent framework can be established. The work conducted by Sarhan and Fox in 2013 is selected since it is more closely aligned with the project management framework that is thought to be useful. The re-organized framework is shown in Table 2.

From the 29 total barriers identified by the literature review, 21 factors can be clustered by their proposed category. The authors kept some of these factors and their definitions, with some minor refinement, to overcome the overlaps identified. All barriers related to the construction industry’s fragmentation, which are pertinent to different procurement methods, are grouped to form the main factor of “fragmentation and procurement.” This category covers six barriers to lean adoption: multi-layer subcontracting, lack of integration of the production chain, poor communication between parties, hierarchies in organizational structures, inadequate delivery performance, and High turnover of the workforce.

Barriers focused on the design and construction segregation create the second category, design/construction dichotomy, which includes minimum involvement of construction participants in the design process and complete designs. The integration between design and construction could eliminate waste, such as incomplete and inaccurate designs; rework in design and construction; lack of buildable designs; final products with significant variation from values specified in the design; and disruption to contractors due to design changes made by designers [20].

Culture and human attitudinal issues targeted any cultural, philosophical, and attitudinal barriers hampering lean practices’ successful implementation within firms. Unwillingness to change, lack of long-term philosophy, and lack of awareness among project participants are among the barriers in this category. Lack of resources, namely time and funding, is the next category that prevents lean adoption. Assigning a

Table 2 Proposed framework

Main factors	Barriers	References
Fragmentation and procurement	Multi-layer subcontracting	Forbes et al. [9]
		Shang and Peng [24]
	Lack of integration of the production chain	Sarhan and Fox [21]
	Poor communication between parties	Abdullah et al. [1]
	Hierarchies in organizational structures	Shang and Peng [24]
	Inadequate delivery performance	Shang and Peng [24]
	High turnover of the workforce	Shang and Peng [24]
Design and const. dichotomy	Minimum involvement of construction workers	Sarhan and Fox [21]
	Complete designs	Sarhan and Fox [21]
		Shang and Peng [24]
Culture and human attitudinal issues	Resistance to change	Shang and Peng [24]
	Absence of the Lean culture in the organization	Sarhan and Fox [21]
		Shang and Peng [24]
	Lack of long-term philosophy	Shang and Peng [24]
	Lack of requiring team member to adopt lean	Sarhan and Fox [21]
	Lack of teamwork	Sarhan and Fox [21]
	Avoid making decisions and taking responsibilities	Sarhan and Fox [21]
		Shang and Peng [24]
	Using relationships to conceal mistakes	Shang and Peng [24]
	Employee tolerance of untidy workspace	Shang and Peng [24]
	Lack of customer-focused measurement	Sarhan and Fox [21]
	Less personal empowerment	Shang and Peng [24]
Resources	Lack of financial resources	Sarhan and Fox [21]
	Lack of time	
Management commitment and support	Lack of manager support	Bashir et al. [5]
		Shang and Peng [24]
	Lack of proper planning and control	Sarhan and Fox [21]
	Poor project management	Abdullah et al. [1]
		Shang and Peng [24]
Skill and knowledge	Insufficient knowledge of Lean	Sarhan and Fox [21]
	Lack of technical capabilities	Sarhan and Fox [21]

(continued)

Table 2 (continued)

Main factors	Barriers	References
	Inadequate training	Shang and Peng [24]
External agencies	Stringent requirements and approvals	Shang and Peng [24]
	Lack of support from the government	Shang and Peng [24]
	Quality of materials	Olatunji [17]

sufficient budget and time to train both employees and employers is necessary for successful lean implementation. Some barriers are related to the management commitment and support of adopting innovations such as lean principles [19]. Ultimately, there are some barriers against the successful implementation of lean, which are not within the control of firms, like stringent requirements and approvals and lack of support from the government. The categories were modified to the new format as listed in Table 2.

There are several suggestions in previous studies addressing the measures that can be applied to overcome these barriers. For instance, Ayarkwa et al. (2012) identified 17 actions that could overcome potential obstacles to implementing lean practices. The five most notable efforts to overcome barriers in the Ghanaian construction industry are:

- Management should train employees on lean concepts;
- Communication should be improved among players in construction projects;
- Construction should ensure or maintain continuous improvement: thus, reduction of costs, increase quality and productivity;
- Construction managers should be committed to changes; and
- Workers should be able to work in teams.

The findings of this study confirmed the steps proposed by Bashir et al. [5] to overcome barriers to the implementation of Lean Construction (LC) in the UK include "taking full advantage of staff training on LC at all levels," "engaging skilled site operatives," and "promoting the LC concept to companies, professional bodies, and major stakeholders" [5].

6 Conclusion

Previous literature has identified several structural and cultural barriers preventing the successful implementation of lean concepts. However, a comprehensive review of the studies conducted in this area reveals that they tried to identify and assess the possible barriers to Lean Construction (LC)'s successful implementation, mainly within the organization level targeting the main contractor's firms. In comparison, the construction trades are at the critical interface where the application of lean methods and principles offers the most value to the construction industry. Therefore, to encourage all industry participants to implement lean, identifying the barriers that hamper the implementation of lean principles is indispensable at the trade level.

Thus, the present study informs the development of pathways and measures to support broader trade contractor adoption to overcome the noted barriers. A full list of common barriers, the frequency of use, and their relative importance, were extracted. Seventeen of these barriers appear commonly in the previous studies, while 12 of the barriers were identified in a survey conducted by Shang and Peng [24]. By inspecting the relative ranking of each, "lack of teamwork," "multi-layer subcontracting," "lack of long-term philosophy," and "absence of the lean culture in the organization" pose the highest mean values, respectively, as the significant barriers to the successful implementation of lean. In this viewpoint, targeting barriers with a high ranking is of substantial importance to answer the fundamental research question of "How to overcome the barriers to the successful adoption of Lean practices."

The lack of focus on trade contractors attracts attention as a remarkable shortcoming. Although some of these barriers can be related to trade contractors, no previous study was found to directly link barriers to the trade contractor community. This study listed the barriers relevant to the trade contractor's considerations, which need to be addressed so they could more easily adopt lean practices. These barriers are

- Lack of teamwork;
- Lack of technical capabilities;
- Poor communication between parties;
- Minimum involvement of workers;
- Lack of production chain integration;
- Quality of materials;
- High turnover of the workforce; and
- Employee tolerance of untidy workspace.

Comparing the context where these studies took place, several studies have been conducted in the UK. There are also other surveys performed in China, Chile, and Ghana. Yet, there is a lack of assessment of obstacles in the United States (US), which is the focus of this research study. Since the practices and approaches implemented in each country might be distinct, a need for a refined categorization of a holistic assessment of barriers in the US is felt.

Last, the majority of the previous studies are framed at the organizational level rather than the project level. They aim to support organizational managers rather than the field workforce, which, according to previous lean literature, should be the focus if the adoption of lean is the true purpose.

Acknowledgements This research was supported by Lean Construction Institute (LCI) and the project Industry Advisory Group, who offered their time to participate and help in this research investigation. In addition to acknowledging their input and support, the authors also would like to thank the Partnership for Achieving Construction Excellence (PACE).

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System Architecture for Supporting BIM to Robotic Construction Integration

A. McClymonds, R. Leicht, and S. Asadi

1 Introduction

The construction industry has progressed at a slower rate than other industries such as manufacturing and industrial sections in terms of technology adoption, more specifically, robotics. However, robotics are becoming more commonplace in the construction industry, with multiple companies developing targeted robots for construction tasks. Some of these robots are made for a single task, such as the Semi-Autonomous Mason (SAM100) made by Construction Robotics or Tybot made by Advanced Construction Robotics. Other robots complete more general tasks, such as Spot by Boston Dynamics. These robots can carry out tasks that can help the construction industry's current labor shortfalls or address human-worker safety challenges. Despite this potentially valuable contribution, the transition from craft labor to robots' use requires a change in the required information provided. One of the fundamental issues is how the robot receives, interprets, and uses the information from a facility design to execute construction tasks to the same degree or scope as craft laborers, showcasing a need for technology infrastructure to support this information transfer.

To create the appropriate technology infrastructure for delivering information for robots to use the building information model (BIM), it is essential to understand the elements that make up a system architecture. A system architecture is a conceptual model that defines the system's views, behavior, and structure. System architecture can be defined as the conceptual model of a system and then models derived from

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S. Walbridge et al. (eds.), *Proceedings of the Canadian Society of Civil Engineering Annual Conference 2021*, Lecture Notes in Civil Engineering 247,
https://doi.org/10.1007/978-981-19-0968-9_18

it. This aspect of the system architecture will represent the different views on top of the conceptual model, facets or concerns of the system independent of the scope and abstraction level of various stakeholders, restrictions for the deployment of the system, description of the quality warranties of the system, and embeddings into other (software) systems [6]. The system architecture is a critical underlying element of the BIM to robot construction information transfer because this is how the robot will receive specific information to carry out its tasks on the job site.

2 Methodology

This paper will present the system architecture and mapping required to support BIM to robotic construction information transfer for in situ construction. This will be done by analyzing examples in the literature to identify both necessary components for the system architecture, as well as define the interactions needed for the information flow; a new system architecture is defined based upon these analyses, which will consider the information needs of the construction industry embued within it. The method will be validated through a simulated test case to verify the system architecture's links, components, and structure.

The literature review research for this paper consisted of two primary literature searches. The first search was for the construction system architecture, and the keywords for the included construction system architecture, BIM, construction, system, and architecture. This phase utilized google scholar as the primary location to receive papers. Papers first were filtered by date in the range from the year 2000 and onward. After that, the reviewed papers would contain the keywords and wherein this timeframe. The next step was to determine if the study had relevance. The abstracts were the starting point for this and were reviewed for verification of focus on information architecture and relevant information exchange support. If the abstract was deemed relevant to the paper, a full review of the paper followed. The second literature search was to identify examples of the robotic system architecture. This literature review involved the same criteria showcased for the construction system architecture; however, the keywords differed focused upon robotic, computer, system, and architecture to search.

3 Literature Review

The system architecture is an essential step in having robots contribute to on-site construction activities. This section will focus on the pre-existing system architectures for BIM within the construction industry and comparable systems to determine the need for robotic system architecture. The new BIM to robotic system architecture presented in this paper used both robotic and BIM system architectures to develop it.

3.1 Construction System Architecture

Kim and Russell [10] focused on the system architecture for an intelligent earthwork system. This study explored the phases of earthwork for construction, including site preparation through finish work. Following the phases, the authors defined the factors that impact earthwork tasks, such as site conditions, work type, and managed work. The data flow is organized into the system architecture module for the task identification and planning and used to determine resource allocation and then the task execution once all the data has been input. This study found that the system architecture will contain three main sections: the task-planning subsystem, task-execution subsystem, and the human control subsystem.

Similarly, Dakhli et al. [4] developed an intelligent construction site's information system architecture. This study determined that the construction resources will have intangible qualities, such as cost, time, weather, material resources, and human resources. Sanguinetti et al. [14]. proposed a system architecture to analyze and give feedback in architectural design. The system architecture structure adapted to various analytical models, such as an energy analysis. While this study is not directly related to robotics in construction, a few constants identified for extracting information from BIM are: (1) It is dependent on the level of detail in the model, (2) External factors can influence the analysis, and (3) Data extraction of the geometry of the structure is of the utmost importance to better refine the process to perform an accurate analysis. A study by Ibrahim et al. [7] developed a conceptual framework for BIM system architecture. Their model defined four phases that the data will progress through (1) Extracting data, (2) Integrating data, (3) Analyzing data, and (4) Interpreting the data. The fundamentals from this study are that the data collected from the model is of high importance, then the information is processed, analyzed, and finally, humans interpret the information from the computer. The main point that this paper is trying to make is that once the data is collected, it must be post-processed to be adequately utilized. Aleksandrov et al. [2] addressed a similar point which where they determined the four main steps for the system architecture are inputting the data, structuring the data with databases, updating the structured data, and finally, data visualization. Another study looked at system architecture for building information modeling and geographic information systems. This study looked at various architecture data integration such as schema, service, ontology, process, and system. This study has a similar method to the rest for the architecture but limited the steps to three: extract, transform and load the data [9]. Bilal et al. [3] looked at significant data architecture for construction waste analytics. The focus of this study was incorporating the modeling information with the big data architecture, and the was analytics to produce results. For this research, the big data architecture had three layers: the storage layer, the analytics layers, and the applications layer. These layers allowed the information from each to be shared while receiving data from various sources.

Based on the studied construction system architectures, a few elements were identified that will be necessary for the BIM to robotic system architecture: the data extraction and structure of the data output is of extreme importance, external data sources utilized, such as site conditions, and the need for post-processing the data. A system architecture for construction applications can be developed from here while addressing the limitations of the previous studies. For example, most of the studies reviewed here focused on BIM or big data system architecture, with the result to visualize the data not having a robot carry out the applications [3, 7, 14]. Therefore, it is imperative to identify robotics system architecture.

3.2 Robotic System Architecture

In addition to system architecture from related construction technology, robotic system requirements will play a critical role in developing a BIM to robot system architecture. Ahmad and Babar [1] studied a basic system architecture for robotics applications. This study evaluated the different sides of the robotic system first by examining a software platform where the application is determined and moves into the control system where the robotic operates. Their research determined three parts to their system architecture: robotic operations, robotic evaluation, and robotic development. Operations focused on the coordination of the robot, evaluation was for the robotic adaptations and reengineering of the task, and finally, development was for programing/data inputting [1]. One study focused on sensor fusion-based robotics system architecture with human interaction. In this study, the robot's system architecture depends on retrieving the information from sensors and then having the system data infused into it through the robot operating software (ROS). After that, the robot would check to see if the inputted commands were feasible to be carried out; if so, the command would then be executed [13]. Another study in the robotic system architecture field focused more on the system architecture for a swarm of robots. In the model presented by this study, the system architecture had a task demand and decision layer heavily reliant on the human–computer interaction; after that, it would go into the planning and execution layers. Each layer inputs sensor data as needed to aid with future decisions and carry out work [12]. Another study focused on robotic system architecture was completed by Jahn et al. [8], which focused on system architecture for modular robotic usage. Their proposed architecture had three layers: the controller, the reflective operator, and the cognitive operator. The control is responsible for the sensors and actuators on the robot, i.e., the data collection. The reflective operator is in charge of processing the data from the controllers. Finally, the cognitive operator is responsible for optimizing the behavior of the system. Integrated into either operator layer is a human–computer interface.

Examples of robotics system architecture can also be identified outside of the construction industry and can play a significant role in creating a system architecture for robotics in the construction industry. One paper looked at modular system architecture. The architecture identified three primary levels: the application level, fusion level, and sensor level. The application-level gets carried out when the data gets delivered for the application. The fusion level is when the data is verified and incorporating the data. The last level and the first carried out is the sensor level. This level picks up the raw data for the application and filters it during the fusion level [5]. This architecture is similar to the other robotics systems in its levels, where the sensor level lines up with extracting data, the fusion level lines up with the integrating data, and the application lines up with analyzing and interpreting data in Ibrahim et al. [7]. Another modular system architecture with a similar design is in a study by Klose et al. [11]. This study examined the modular system architecture for an autonomous robot for plant evaluation. While this study did focus on plants, the basis is applicable for construction application. The main aspects discussed are sensing the data, storing the data, and analyzing the data. Building upon these functions, the robot control system becomes paramount. In summary, the overall process is proposed by sensing the data and collecting it, then using that information to control the robot [11]. Another type of robotic system architecture is cloud-based robotics—a study by Wan et al. [15] looked at defining the system architecture and identifying issues associated with it. For the system architecture of cloud robotics, they have data collection, data storage, database integration, and carrying out the robotic task while all steps provide feedback. A few of the critical issues this study identified are resource allocations, data interaction between robot and cloud, and security concerns [15].

These studies can lead to a few general consensuses about robotic system architecture. One is that there is a constant influx of data into the system. This can be from a variety of different sensors and actuators on the robot as well as external sources. Another is an output responsible for executing tasks and other data collection that a human can interpret. A critical aspect is the control of the robot. The control gets carried out by different simulation software, such as ROS. Therefore, the robot will be in an eventual loop of planning, sensing, and executing tasks as a simple model. The loop identified creates a system architecture that will allow for BIM to robotic interaction. Based on the robotic system architecture shown, elements have been identified necessary for the BIM to robotic system architecture. These elements are extracting data, integrating the data, and analyzing and interpreting the data [5, 8, 11]. However, these studies are limited in nature as they do not directly relate to integrating a BIM model for the robots data collection. Most of these studies had large amounts of their data come from sensors, which will be needed but will also need information about the task from the model.

4 System Architecture

Based on previous studies, a system architecture for BIM to robot construction is developed and a similar in design as proposed by Kim and Russell [10]. This model will have three different and equally essential phases, including task planning, task decomposition, and task execution, to send the information from a BIM model to be executed by a robot. Figure 1 shows the overall system architecture for supporting BIM to robotic construction integration developed in this study. This method is dependent on a BIM model of sufficient detail for construction purposes.

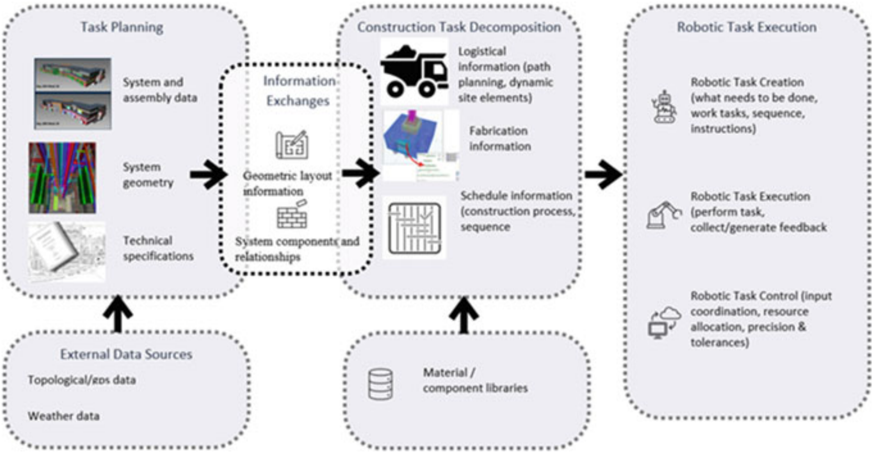

Fig. 1 BIM to Robot System Architecture

4.1 Task Planning

The first phase of the system architecture to take place is the task planning phase. The task planning phase is shown in Fig. 1. Information is gathered from the project to determine what work will need to be completed. Therefore, this phase aims to determine the system that will be constructed and collects information about the facility and site. The task planning phase's first step is to determine what task, system, or activity will be carried out by the robot. The second step of this phase is to extract information about the chosen system(s). Information from the system will be analyzed, including system geometry, system tolerances, system specifications, adjacent systems, and connected components. These aspects must be considered for the system architecture to provide information for downstream functions, as each facility subsystem will have its own requirements and constraints. For example, looking at ductwork in the building from the mechanical design, the ductwork system is often defined to a higher level of detail to support fabrication than many other systems in the building. Further, it also interacts with numerous other building systems, such as the other electrical and structural systems. Where the ductwork interacts with these systems must be taken into consideration as it could influence the sequence of work. Also, ductwork in the building is not a constant size and interacts with different ductwork types. Depending on the building type, tolerances can also be quite strict on this system as well. Other aspects external of the system must also be considered, such as the topological data, site hazards, weather information, and storage information. With ductwork, the robot would need information regarding the components and data to transport the correct piece to the needed install location. These external data sources are allowed for proper site planning. Determining this information early in the process is critical to the success of the system architecture.

4.2 Task Decomposition

The second phase of the system architecture is task decomposition. This phase is also shown in Fig. 1, occurs once the task planning phase is complete. The purpose of the task decomposition phase is to determine and formalize the logistical steps associated with the task or system assembly chosen in the previous phase. There are three main subtasks associated with this phase which are (1) logistical information, (2) fabrication information, and (3) scheduling information. The logistical information primarily incorporates the data extracted or generated in the previous phase, such as storage locations, site hazards, and facility geometry. It will also incorporate dynamic aspects of the site, such as moving construction equipment. The tasks in this phase allow for the robot's path planning in a later phase of the proposed system architecture. The second task in this phase is for fabrication information. This task refers to systems that require additional fabrication before being installed. In current processes, the specifics for fabrication are often left to the contractor. Building upon the ductwork, the flange or other connection interface between two sections of ductwork would be defined and incorporated at this stage. The final task in this phase is to determine the scheduling information for the chosen task and corresponding system components. The schedule for the task will be determined by analyzing the construction process and sequence. The analysis will consider the overall facility systems and how the subsystems relate to the task chosen, including duration, resources, and imposed site constraints.

Ductwork is a prime example of the task decomposition phase because of the proximity to numerous other building systems. First, the general process for installing one piece of ductwork can be clearly defined. From there, the method expands to allow the installation of subsequent pieces of ductwork. Some pieces will have to be installed into the structure earlier or later based on the building's location and the building systems. Therefore sequencing of the work must be taken into consideration. If not done correctly, it could potentially cause delays for other trades on the construction site. This phase must consider the dynamic nature of the construction site.

4.3 Task Execution

The task execution phase is the last phase in the system architecture. This phase is shown in Fig. 1 as robotic task execution. Task execution is based heavily on the work done by Ibrahim et al. [7] and Sanguinetti et al. [14] to provide the information and data collected from the previous phase to the robot to carry out its task. This phase contains three main tasks: robotic task creation, robotic task execution, and robotic task control. These tasks work in conjunction to allow the robot to carry out its task and provide feedback to the operator to improve future construction work. The robotic task creation relies heavily on the scheduling and logistical information determined in the task decomposition phase. The schedule determined in the previous phase will give the robot the order of operations to carry out its task and the logistical information to define the locations for that task on the job site. The next task is the robotic task execution. During this part of the phase, the robot will carry out its task. It will interpret the control's commands and receive the information from the task creation task. With this information, the robot will carry out its task and then identify which subsequent task to complete. Task creation will further allow the robot to generate a construction report that provides feedback on the construction site or reports errors in the process. The final task to be discussed in this section is robotic task control. Task control takes the information from the task creation and inputs it to the robot allowing the task execution to result in the performance of work on the project. It will receive information from the task execution, letting the robot know if the previous task was completed and completed correctly. If completed correctly, it can then send the command for the next task to the robot. This task will also take into consideration aspects such as tolerance to ensure the quality of the job. These tasks will continue to work together until the last task gets completed. Revisiting the ductwork example for this phase is critical. The robot must receive the information from the previous steps and install the ductwork into its final location. It must be able to identify the correct piece at the correct time and ensure proper installation. The robot must also identify if this work is correct to ensure quality. If the panel was missing or not correctly installed, the robot should identify this and adjust to this.

4.4 Information Exchanges

The information exchange is a critical aspect of the system architecture. One of the information exchanges is highlighted in greater detail than the other in Fig. 1, but it takes place between each phase of the system architecture. The information exchange between the task planning phase and the task decomposition phase is highly dependent on the task or system was chosen for the system architecture. The information exchange depends on the task and is also subject to constraints based on the BIM model's level of development for a specific component or assembly. The information exchange allows for the information that was initially included in the BIM model to be extracted and augmented to support the task decomposition phase. Continuing with ductwork as a prime example, while sufficient sheet metal information may be present in the model for the system, items such as hangers may not be represented in the model. This information is an example of supplemental information that may just be expressed as a note or in the project's specification. Information on how different systems interact with the ductwork may need to be added as well.

The other central information exchange takes place between the task decomposition phase and the task execution phase. This information exchange aims to take the schedule, logistical, and fabrication information and convert it into a form easily interpretable by the robot. The robot will need this information to carry out its task and use all the information collected by the system architecture's previous two phases. As noted, the task execution needs the scheduling information, site information, and an understanding of the construction process. Some of this information will have to be continuously updated based on the site's dynamic nature. Looking at the site information as an example, material, equipment, progress on other systems, and site conditions is constantly changing. This information gets relayed to the robot. Also, depending on the robotic system-specific file types may have to be used to allow the robot to interpret the assembly instructions. To briefly revisit the ductwork example, the information needed for location and interaction with other systems is sent to the robot. However, the ductwork may be threaded through a truss or an opening in a wall. This information must be detailed and structured to allow the robot to install the components correctly.

5 Case Study

This case study considers the simulated use of a robotic method for setting masonry blocks, specifically for concrete masonry units (CMUs). This section will use the case study to validate how the BIM content gets translated into robotic tasks with the system architecture laid out in the previous section. To begin, after the specific task is chosen, it is essential to understand how it gets accomplished traditionally. This case would consist of gathering the material and tools, laying out the wall, determining the start location, placing mortar to the CMU's bottom, placing the CMU, and finally repeating for each brick after. At this time, gathered data determines weather and topological data of the construction site. Technical Data from the specifications will get gathered. This data will include information such as tolerances associated with the construction (e.g., the spacing between bricks), types of allowable materials for construction, and other design or quality performance details. The system's general layout will also be extracted from the BIM model to determine component layout and orientation.

The information exchange exports the model content, geometry, and supporting data. The first activity is to determine what information must be supplemented to the BIM model, and in this case, it would be for a CMU wall. In most BIM software platforms, such as Revit, sub-assembly components, such as individual CMU blocks, are not typically individually modeled, and therefore are not split into separate components. This lack of detail raises an issue because the robot will need to know the count, spacing, and orientation of the blocks and their exact location on the construction site to place the block precisely. Therefore, external data must be utilized to determine this, or each block can become a model. There are numerous ways of accomplishing the additional information. One method of accomplishing this would be to manually add the information to the model or take an automated approach by having an interim step to decompose the model and surface hatching to define sub-components. Once the model has the supplemental information, it will be converted into a format that the robot will be able to read. In the pilot, the data was translated into a.csv file, similarly an.IFC file could be considered. A map of the site should be created and available during this phase. This map can act as an occupancy grid to work in tandem with sensors on the robot to prevent a collision with fixed or stationary objects within the construction zone.

From here, the system can move into task decomposition. Since this task needs very little fabrication information, this case study will skip that aspect of the proposed system architecture. The crucial part of this phase would be determining the task scheduling information for the robot. The schedule needs to contain the order in which each block gets placed so that the wall will be correct and structurally stable upon completion. For example, the robot would start work at an initial corner, go to a doorway or a place toothing may occur, and then return to the initial corner to lay the next course. From there, it would continue along the wall to a set stopping point. The robot repeats for each course until there are no more blocks to place. To simplify, a schedule for the bricks gets developed utilizing typical industry standards to describe laying a course of brick. This schedule seems logical for a human worker, but it will need to be programmed for the robot to carry out this task. Once this is determined, the robot's route to transfer can be determined based on different construction site obstacles.

The last phase of the system architecture for the BIM to robot integration is the task's execution. During this phase, the data collected or added from external sources for the model is transmitted to the robot. Through coordination with other craft or on-site workforce, the robot will navigate its path to carry out the task of gathering blocks and moving them to their install location. The bulk of the information will come from the schedule, including each of the blocks' orders and locations. The occupancy map would then allow the robot to understand the site based on a coordinate grid. However, an issue can arise with the occupancy grid because the construction site is dynamic. The construction site's dynamic nature results in the occupancy grid's need to evolve and adapt to the construction's progression. This occupancy grid allows the robot the ability to carry out its assigned task. While the robot is carrying out its task, it is essential to determine if the job is being done to the design specifications, ensuring that the blocks are correct and not missing. Therefore, the robot will need to provide feedback on the wall's progression to the site workers.

6 Discussion and Conclusions

This study set out to create a system architecture for BIM to Robotic Construction Integration and accomplished this by reviewing literature into construction system architecture and robotic system architecture, then piloting it for a case study. From there, aspects of typical system architecture were determined and used to create the proposed system architecture. For the construction system architecture, the parallels between the studies presented found that the data collections are of extreme importance, external sources taken into account, and a human aspect involved. For the robotic system architecture, the parallels are as follows: there is constant data flow within the system, humans oversee executing tasks and data collections, and there is a control module for the robot. These system architectures influenced the system architecture presented in this paper by (1) providing insight into how the robot interprets information providing the final phase of the system architecture presented, (2) providing a basis to how BIM system architecture gets typically accomplished, and (3) where and when information gets supplemented. The method developed integrates both of these types of system architectures. The method is broken into three major phases: task planning, task decomposition, and task execution. These phases' descriptions are in detail above and state what would take place in each phase. After which, a case study got presented utilizing the various aspects of this system architecture.

However, a few areas that need to be further developed were identified from the case study. One was with the initial stages of the information exchange because of the lack of information in some BIM model systems; however, the system architecture utilized the areas that require the supplemental information will be determined. This information can then be added to the model in a format accessible by the robot. Some systems, such as MEP, may contain extensive detail, while others, such as blocks wall, may not. Another point for further consideration is the recognition of the dynamic nature of the construction site. Since the site changes daily, and in some cases constantly, there will be a need to navigate obstacles for the robot.

Some areas for future work include investigating the information exchange and methods to supplement design model data, leaving room for a more standardized process. Also, work on how site utilization plans can be developed as smart rather than passive elements may offer solutions to site navigation for robots.

The proposed system is not without its limitations. It is constrained by limitations associated with this software. Another limitation is that the proposed method focuses mainly on all systems in general. As shown by the case study, different systems will have different requirements, data sources, standards, and practices resulting in aspects of the architecture that must be flexible. The final limitation is what robot gets chosen for the last section of the proposed system architecture. Each robot will have different capabilities and its own set of limitations. These limitations need taking into consideration for the proposed method to be successful.

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Integration and I4.0 Tracking Systems for Steel Manufacturing Industry

S. Rankohi, M. Bourgault, I. Iordanova, C. Danjou, P. Garcia, and J. Grondin

1 Introduction

Industry 4.0 consists of advanced technological opportunities and management strategies, which aims to provide new business models for the manufacturing industries [12]. A key technology for industry 4.0 is the Internet of things (IoT). According to Atzori et al. [4], digitalization through IoT can be achieved in three paradigms: internet-oriented (middleware), things oriented (sensors), and semantic-oriented (knowledge). In application domains where the three paradigms intersect, the usefulness of IoT can be fully unleashed [5]. Tracking material for the steel manufacturing industry is an example of such application domain, in which IoT can significantly improve the current traditional procedure.

The growing needs for digitalization and automation in steel manufacturing industry, along with the difficulties in the current traditional procedure of steel fabrication and delivery, motivated the authors to propose an IoT architecture, which supports digital and automated tracking of structural steel products. More specifically, this paper presents a multi-layer IoT architecture which is applied in a case study,

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S. Walbridge et al. (eds.), *Proceedings of the Canadian Society of Civil Engineering Annual Conference 2021*, Lecture Notes in Civil Engineering 247,
https://doi.org/10.1007/978-981-19-0968-9_19

through designing data collection, transmission, and analyzing web-based applications for steel products tracking, as well as knowledge reuse for inventory management purposes. Finally, the impact of this digital procedure on project integration (horizontal, vertical, and longitudinal) has been discussed.

2 Background and Motivation

The Internet of Things (IoT) refers to several heterogeneous intelligent objects (things) that are fully interconnected, and capable of communicating through the Internet using various protocols [14]. The IoT provides new capacities to the "things" including remote actuation to interconnected devices through wireless networks and smart sensors [8]. Smart sensors along with cloud computing took the market in various areas including retail, asset tracking, logistic, inventory management in supply chains, and production lines [14]. This paper proposes an innovative solution based on IoT, cloud computing, and RFID technology for identifying, tracking, and positioning steel products, which has been successfully developed and piloted in a steel manufacturing warehouse.

2.1 IoT and Tracking Technologies

Multiple tracking technologies are currently being applied in the manufacturing industry, such as Bluetooth, GPS, QR code, WiFi, etc. The proposed technology for tracking of steel products in this study is RFID, which stands for Radio Frequency Identification. RFID is a method for storing and retrieving remote data using antennas called "RFID tags". These tags are small objects, such as self-adhesive labels, that can be stuck or incorporated into different objects. As shown in Fig. 1, once tags are triggered by an electromagnetic pulse from a nearby RFID reader device, the tag transmits digital data (such as an identifying number) back to the reader.

There are two types of RFID tags: passive and active. Passive tags are powered by energy from the RFID reader's interrogating radio waves, while active tags are powered by a battery and thus can be read at a greater range (up to hundreds of

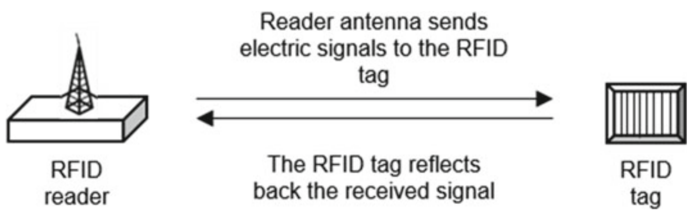

Fig. 1 RFID reading process

meters) from the RFID reader. In this study, we chose passive RFID due to two reasons: (a) reliability: this technology is very robust and it has been widely used for industrial applications with satisfactory results, (b) price: passive RFID tags are less expensive than other similar technologies, such as UWB (Ultra-wide-band).

We conducted a case study on a steel manufacturing plant similar to the study performed by Valente and Neto in 2017. We have selected a Canadian steel manufacturing plant, to explore the application of IoT for improving inventory management practices for a particular structural steel bar product in the plant warehouse. The company produce many of these steel bars per year, and loss significant costs with its current traditional inventory management process. Based on the proposed IoT solution, the steel bars will be tracked with RFID technologies, allowing inventory managers to save time and cost by accessing real time digital information of their inventory.

3 Proposed IoT Architecture

3.1 Identification of Transformation Objectives

To conduct this case study on the application of IoT and RFID technologies for inventory management, we have selected a special steel bar product. The selected steel bars are temporary support required during the installation of other structural steel elements, and they have to be returned to the plant after being used by the client onsite. During the process of sending, installing, and returning these steel bars, many of them have been lost, damaged, or stolen; making the company to undergo significant annual costs to replace them. The inventory management process of the selected steel bars was significantly manual, time-consuming, and error-prone as well. The company was continuously looking for possible approaches to improve and automate the warehouse management process using industry 4.0 technologies.

In order to understand the digital transformation objectives for transforming the steel bar inventory, we have conducted virtual and physical observations, interviews, and a Kaizen blitz with the plant director, inventory managers, and employees. During the observations and interviews, we investigated the existing problems for the inventory management, collected evidence, and gathered information to categorize deficiencies and define improvement objectives. Table 1 summarizes the main problems and associated objectives that have been identified during interviews. In order to identify the improvement areas, we classified the objectives under process, product, and service.

We have conducted a Kaizen blitz with plant stakeholders, to visualize inventory management steps and identify process "wastes", such as over-production, over-processing, lost time, poor service, extra inventory, and information gaps. As shown in Fig. 2, we focused on bars' return management process (as it was the area where most issues belong to), and developed planning steps diagram in a push/pull similar

Table 1 Steel bars inventory problems, improvement goals, and objectives

	Improvement area	Problem	Objective
Product	Steel bars	High annual loss, and expensive fabrication costs	Reduce fabrication costs by: automatic tracking of returned bars, real-time clients updating of the missing pieces, and increase clients responsibilities
Process	Inventory management	Manual and inefficient inventory management process	Reduce inventory management costs by having less manual works, through automatic tracking and inventory monitoring and control
Service	Rental services for the clients	Costly service, broken lines of communication with the client for returning steel bars	Improve quality of service to the clients by developing a mobile application which can provide access to bars information i.e., delivered and returned steel bar types, quantities, number of racks, BOLs, costs, etc

format. The color-coded boxes represent steps that could be eliminated or improved through a digital transformation of the inventory. The blue boxes represent steps that could be improved/eliminated by a tracking system that the company's employees could use; while grey boxes represent those steps that could be transformed if clients could use an online or mobile steel bars tracking application. As shown, color-coded steps represent more than 50% of the total tasks. This means there was more than 50% chance of increasing the efficiency and improving the whole process.

Based on the results of the Kaizen blitz, we came up with the idea of developing a steel bar IoT tracking application for the company, which could be used by both clients and the bar inventory management team. In terms of the strategic positioning of our proposed solution, as shown in Fig. 3, we consider this tracking application as an improvement to the company steel bar tracking/inventory process, as well as providing a monitoring service for the clients (through a web-based mobile application).

3.2 IoT Architecture

The proposed IoT architecture, as shown in Fig. 4, is developed and implemented in a case study project in the plant. The developed steel bar tracking application is based on using barcodes, RFID antennas, and readers for sensing and collecting data. The data transmission is done by WiFi; the integration layer is covered by the same

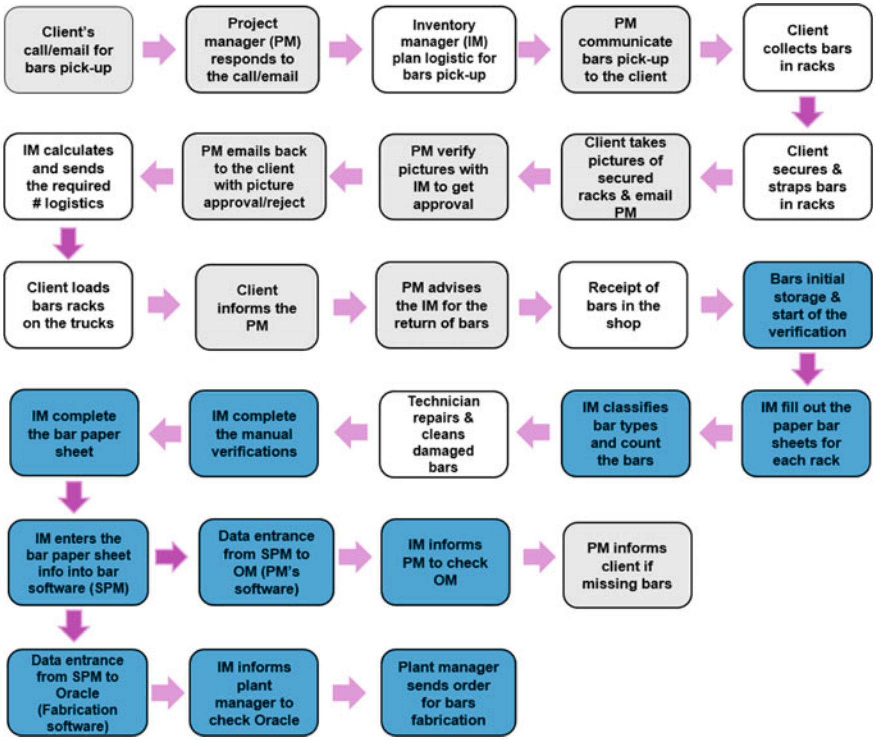

Fig. 2 Steel bar inventory return planning steps (Kaizen blitz)

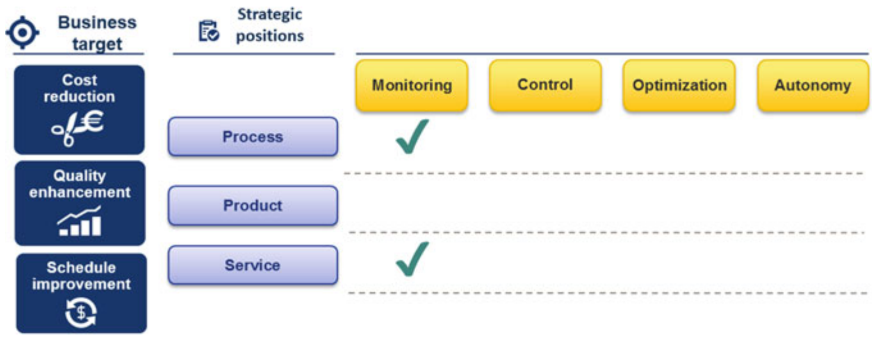

Fig. 3 Strategic positioning of the proposed solution for transforming steel bars inventory

company providing the RFID readers; and finally, analysis and decisions layers are the inventory operators and company engineers' responsibilities. As shown in Fig. 4, the proposed architecture consists of three main layers: *system, network, and service layers.*

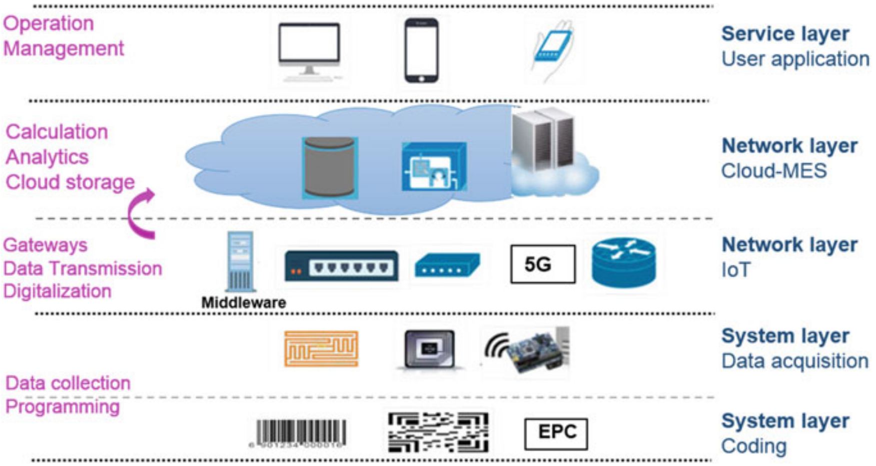

Fig. 4 Main layers of the proposed IoT architecture

The *system layer* consists of coding, information acquisition, and information access phases. In the coding phase, an ID number is assigned to each objects. Then the objects can be recognized in the whole cycle of the IoT. For instance, clients are provided with barcodes (installed on the racks or shown on pdf drawings). They scan these barcodes with their smart phones, which direct them to the company's web-based steel bar application. This application is equipped with mobile tag reader technologies, which are used by the clients to make sure they have collected all received steel bars in returning racks. In addition, clients can use this application to send automated alerts to project managers to inform that the steel bar racks are ready for pick-up. The information acquisition phase is the source of the IoT. In this phase, data is collected and objects are identified via RFID tags.

The information access phase is to transmit the obtained information from the collection phase to the network layer. The information transmission network can be mobile communication network (i.e., GSM, TD-SCDMA, WiMAX, WiFi, etc.). The proposed *network layer* is a network platform, working based on IPV6. It consists of a large intelligent network, which is capable of utilizing all the resources in the network. Within the network layer, we have the information integration layer over the cloud, to manage and control the collected data in the network in real-time. In order to provide a good service interface to the application service layer for the clients, the data is reorganized, filtered, integrated, and transformed into the content service in the SOA. Finally, the *service layer* integrates the service capabilities and provides the application service to the clients.

3.3 Autonomous Process

The proposed autonomous steel bar inventory management process has the following steps:

Step 1: racks full of steel bars pass through the shipping doors located in the inventory shop floor, before being placed on the trucks to be shipped to the site. RFID reader identifies the tags, which pass through the doors. For the reading purpose, tags are placed on each of the steel bars so they all have a unique ID, which contains information such as the type of the steel bar. When the bars are passing through the exit gates, two RFID antennas emit Radio Frequency waves that are captured by the antennas of each of the labels and are returned to the RFID antennas with the information regarding the identification number of each of the bars. This captured information is transmitted from the RFID antennas to an antenna's hub. Each hub can gather information from multiple antennas at the same time. RFID readers read the information from the antenna's hub and a specific software transforms it to be exported. The exported information can be used by the client via online user application, transmitted by API, and integrated with the company's inventory management system.

Step 2: clients receive the steel bars onsite, use them as temporary supports during the installation of other steel elements, and remove them once the installation process is complete. Once removed, the clients put used bars back in racks, scan racks' barcodes with their smart phones, use company's web-based application, upload pictures of loaded racks, enter preferred pick-up date, receive pictures' safety approval note, and the pick-up date confirmation.

Step 3: the returned racks to the shop pass through the shipping doors and the tags' reading information is recorded again by RFID readers.

Step 4: the collected data is automatically transferred to the cloud-based platform, comparison charts are generated, and difference between sent and received bars are calculated automatically in real-time. An automatic notification, which shows the total differences (if any), is sent to the project managers, inventory managers, and the clients.

Step 5: the inventory management team can quickly and easily make business decisions based on the received tracking information (i.e., charging clients who did not return all bars, fabricating the missing bars, etc.).

3.4 Further Applications

In addition to obtaining real-time control over the steel bar inventory, the implementation of IoT in this process helps clarifying the causes of lost or broken bars, optimizing the life cycle of the bars and improving the quality of the final product. It could also be the first step for developing a fully autonomous steel bars inventory processing in the shop, including all steps (inspection, cleaning, classification and decisions) as well as fully autonomous decision-making system such as the timing of increasing/decreasing the steel bar inventory or when to charge a customer. In addition, the same tracking technology can be applied to other company's products. Furthermore, it could help the company to continue with its Industry 4.0 and lean strategy, accelerating the integration of IoT in other processes such as manufacturing, or the global inventory.

4 Discussion

The tracking and monitoring service provided by IoT enables integration with the enterprise systems to support decentralized decision-making activities. The integration of product tracking in the daily operation of a steel manufacturing plant will increase automation levels by reducing manual tasks in various procedure, for instance in inventory management practices [9]. While IoT increases the automation, it also affects the project integration.

According to Kaur and Kaur [7], IoT provides a platform for person-to-person (P2P), machine-to-machine (M2M) and person-to-machine (P2M) communications and interactions (shown in Fig. 5). In this study, we aimed to understand the impact of these interactions on three levels of project integration as described by Oesterreich et al. in 2016. According to Oesterreich et al., three levels of integration are required to implement Industry 4.0 technologies: horizontal, end-to-end digital and vertical integrations.

Horizontal integration (HI) through value networks which refers to the integration of IT systems, processes and data flows between various stakeholders and companies. For example, integration between different clients, suppliers, and external partners enables stronger collaboration with value chain partners across enterprise borders.

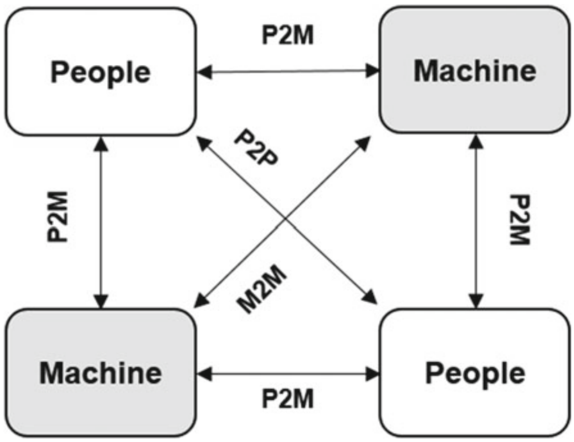

Fig. 5 IoT communication scenarios

In this case study, the proposed IoT solution helped various partners from different disciplines (external customer, internal teams, engineers, and sale department) work together simultaneously and more efficiently. The P2P (i.e., the client to the plant management team, the logistic team to the client, etc.), and P2M (i.e., reader alerts for the missing steel bars to the inventory management team) communication and collaboration over the cloud platform, made the whole process shorter and less error-prone than the traditional method.

End-to-end digital integration (EI) of engineering across the entire value chain results in a reduction of internal operating costs through facilitating highly customized products. In this model, cyber-physical systems are required to enhance digital integration of the value chain. In the conducted case study, the M2M (i.e., automatically printed customized digital BOL) communication improved digital integration through reducing manual paper work, which was being performed by the inventory management team.

Vertical integration (VI) and networked manufacturing systems result in a smart manufacturing environment. For example, integration of IT systems, processes, and data flows within the enterprise business units from product development to manufacturing lines, inventory, logistics, and sales for cross-functional collaborations. In the case study, the P2P (i.e., the plant management to the pre-construction team, the procurement to the design team, etc.), and the P2M (i.e., notification alerts for the shortage of steel bars in the inventory to the design and fabrication teams) communications enhanced vertical integration between various business units. These digital collaborations through IoT platform provided team members with a real-time access to the project information and ultimately reduced the amount of human errors.

As shown in Fig. 6, P2P and P2M collaborations improve horizontal and vertical integrations, while M2M digital communication and collaboration mostly affect the end-to-end digital integration.

5 Conclusion

In this article, the primary goal was to propose an Industry 4.0 solution for improving the traditional process of a warehouse management in structural steel manufacturing industry. In addition, we aimed to explore the impact of the proposed solution on projects integration levels as described by Oesterreich et al. [10]: horizontal, end-to-end digital, and vertical. Based on the outcomes of this research, the following conclusions are drawn:

- The IoT technologies are currently accessible for various industrial applications; however, their widespread adoption by the construction sector has not taken place yet [10]. Studies demonstrate practical ways for the adoption of IoT and RFID tracking technologies to digitise and automate the construction material inventories for fabrication plants. We developed an IoT and RFID tracking system and

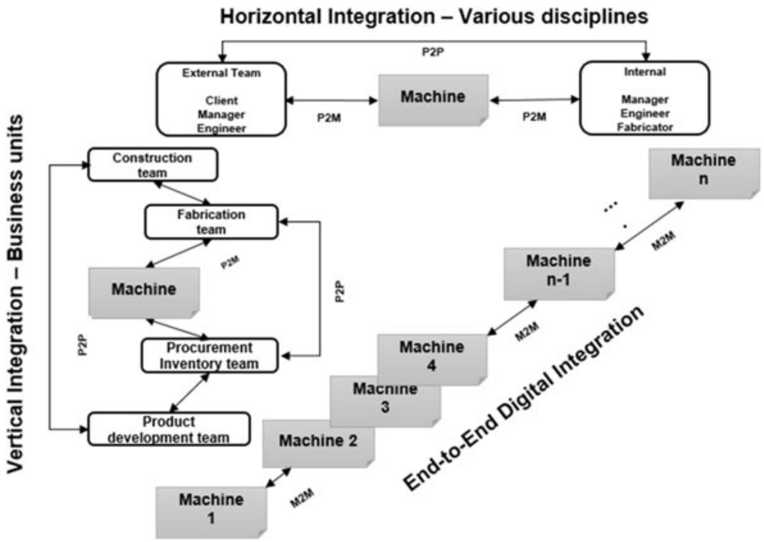

Fig. 6 Industry 4.0 technologies and project integration levels

conducted a case study in a steel manufacturing plant. The results of our case study showed that the developed platform provides new possibilities for digitalization and integration in the steel fabrication industry. The web-based cloud-based automated tracking application helped project managers to reduce project costs and improve the overall efficiency of the warehouse management practices.

- The impact of the developed IoT tracking architecture on project integration has been investigated in this study. As per the results, people-to-people, machine-to-machine, and people-to-machine communications through IoT technologies have impacts on projects integration in the context of industry 4.0: horizontal, vertical, and end-to-end digital integrations. While IoT-based communications can affect all levels of integration, horizontal and vertical integrations are mostly influenced by person-to-person and person-to-machine communications and digital collaborations, while machine-to-machine communication mostly affects the end-to-end digital integration. We have concluded that the digital collaboration provided by the developed IoT solution, improves the integration in our case study project.

It is recommended to conduct further research and studies on different types of projects in order to understand the positive or negative impact of I4.0 technologies and decentralize decision-making strategies on a global integration from a project and organizational point of view.

Acknowledgements The authors would like to acknowledge the support provided by CANAM Construction Group and Pomerleau Industrial Research Chair in Innovation and Construction Project Governance, to conduct this research project.

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UAV Applications in the AEC/FM Industry: A Review

Mohammed Sulaiman, Hexu Liu, Mohamed Bin Alhaj, and Osama Abudayyeh

1 Introduction

In the last decade, unmanned aerial vehicle (UAV) has been increasingly used for the engineering applications in the architecture, engineering, construction, and facility management (AEC/FM) industry [7]. Primarily, UAVs were used for progress monitoring and work inspection, such as construction operation, bridge maintenance, and infrastructure inspection [4]. It is because UAV offers the ability for remote data collection [18]. It is proven to be one of the most economical and effective technologies in data collection, especially for inaccessible areas [11]. The increasing research efforts regarding UAV applications in the AEC/FM industry lead to a large amount of literature. In this context, several reviews were presented in the existing literature to summarize these efforts in this field. However, most of the existing reviews applied qualitative analysis to reveal the research trends and future directions. For instance, Shakhatreh et al. [17] presented a systematic review for revealing the UAV civil applications with their potential challenges. Another qualitative review was also conducted by Albeaino et al. [1]. They reviewed 86 peer-reviewed articles with the aim of classifying the applications of UAV in the AEC/FM domain and highlighting its research trends. In their review, the collected articles were critically analyzed and discussed in terms of inspection of structure and infrastructure, transportation, monitoring work progress, safety, city and urban design, heritage protection, and disaster management. However, such a manual review is a qualitative analysis, and a conclusion is formed based on a limited number of peer-reviewed articles. For this

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S. Walbridge et al. (eds.), *Proceedings of the Canadian Society of Civil Engineering Annual Conference 2021*, Lecture Notes in Civil Engineering 247,
https://doi.org/10.1007/978-981-19-0968-9_20

reason, it fails to provide quantitative insights into the targeted research field. Unlike existing reviews, this research represents a quantitative analysis of the state-of-the-art of UAVs for AEC/FM applications to discover the research trends, challenges, and future directions.

2 Methodology

The research aims to provide quantitative insights into the UAV applications in the AEC/FM industry and reveal the UAV's potentials and challenges in this area. The review in this study is carried out through quantitative analysis (i.e., bibliometric analysis). The bibliometric analysis allows for quantitatively answering the research question of research trends and intensive recognition of challenges and demands of the research related to drone UAV applications in the AEC/FM industry. Figure 1 describes the research methodology. It starts with collecting and retrieving data from the research database. The Scopus database was used in this research because it covers interdisciplinary research and journal papers [10]. Journal publications related to UAV applications in AEC/FM domain were collected using the keywords such as "Unmanned Aerial Vehicle" OR "Drone" and "Architecture" OR "Engineering" OR "Construction" OR "Facility Management" in the Scopus database. It is worth mentioning that the keywords are determined based on existing literature reviews [3, 6, 10, 14]. Furthermore, these selected keywords were used to search the field of titles, abstracts, and keywords sections to identify related journal articles. The search was limited to 10 years of publications between 2010 and 2020, the English language publications, and the field of engineering and computer science. The search initially resulted in 2249 journal articles. These journal articles are refined by choosing the relevant fields such as engineering and computer science. The screening process

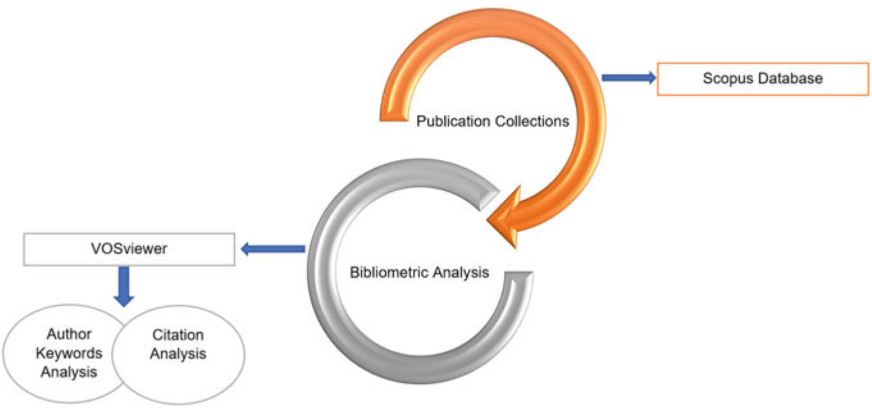

Fig. 1 Methodology

ended up with 552 journal documents. Following that, a bibliometric analysis was applied in order to identify the statistical characteristics of the UAV research publications. This quantitative bibliometric analysis was performed by means of author Keyword co-occurrence and citation mapping. VOSviewer was used for bibliometric analysis because of its ability in performing and visualizing a map of co-occurrence authors keywords and citation map [10].

3 Results

3.1 Keyword Co-occurrence

The keyword co-occurrence network was generated using VOSviewer based on author keywords of selected 552 academic papers. In the VOSviewer, the number of keyword occurrences was set as three, and the percentage of the keywords to be selected was 80%. In addition, all keywords that have the same semantic meaning were combined to enhance the result of the developed map—for instance, UAV and Unmanned aerial vehicles combined with the drone. Figure 2 presents the total of 65 keywords of the 1969 keywords that are included in the co-occurrence network. This network, consisting of 65 keyword clusters and 195 links, represents the major research topics in the UAV applications in the AEC/FM industry. The keyword clusters contain five colors that classified into four groups (1) path planning/collision avoidance (orange and pink clusters), (2) safety (red cluster), (3) data and data

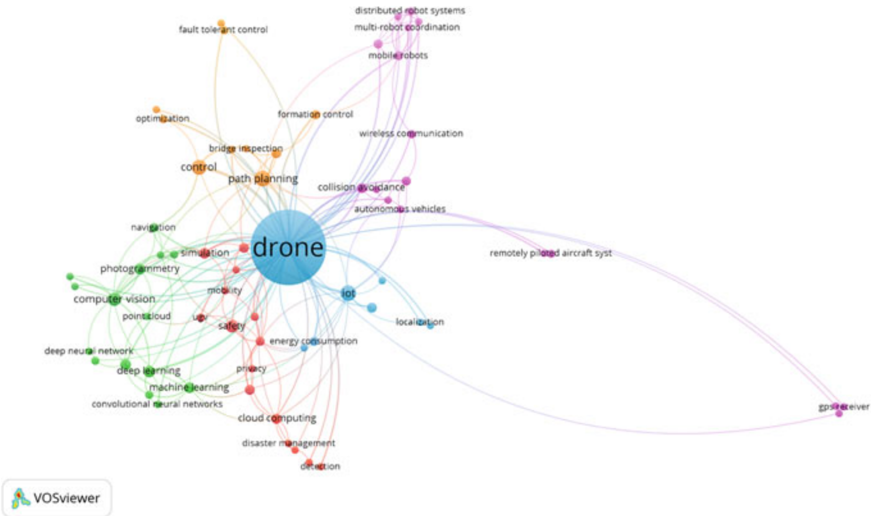

Fig. 2 Author keywords co-occurrence

processing (green cluster), and (4) internet of things (IoT) (blue cluster). Table 1 tabulates the keywords of the co-occurrence network.

3.1.1 Path Planning/Collision Avoidance (Orange and Pink Clusters)

As shown in Fig. 2, many efforts have been dedicated to UAV path planning for the inspection purpose. It results in the largest cluster with frequent keywords of control, optimization, bridge inspection, formation control, fault-tolerant control, distributed robot systems, multi-robot coordination, mobile robots, wireless communication, collision avoidance, autonomous vehicles, remotely piloted aircraft systems, and GPS receiver. This research cluster implies that UAV-based inspection activity is demanded in the AEC/FM industries. UAV path planning was extensively studied to automate optimal flight path planning in consideration of the UAV limitations such as batteries [19]. Also, collision avoidance is studied to ensure the safety of UAV operations during the inspection. Meanwhile, UAV-based energy management has also been studied to achieve better and safer inspection processes, reduce inspection time, save labor costs, and avoid entering dangerous places. As shown in Table 1, the average publication year for "Inspection" is 2019, indicating its emergency in the past two years. On the contrary, the average publication year for "Path Planning" is 2017, suggesting that it has attracted more attention in the past four years. For example, previous studies concentrated on outdoor path planning for UAV operations. In this sense, further research on indoor path planning deserves more efforts to achieve smart indoor inspection using drones in the AEC/FM industry.

3.1.2 Safety (Red Cluster)

Safety is attracting attention for the use of UAVs in the AEC/FM industry. As shown in Fig. 2, keywords such as privacy, security, routing protocols, simulation, mobility, edge computing, cloud computing, UGV, disaster management, and detection are frequently used. In particular, in the occurrence map, safety has the highest occurrence of 9 with the average publication year of 2017 (see Table 1). Moreover, as part of the safety, security keyword has frequently appeared with an average of the publication year 2018 and occurrence of 5. Furthermore, concerning privacy has been used in the average publication year of 2018. A critical challenge of using UAVs is privacy [12], since UAVs are equipped with cameras. Consequently, it is important to consider privacy in the use of UAVs. Furthermore, the keyword of routing protocols is related to UAVs in the AEC/FM industry with an average population year of 2018.

3.1.3 Data/Data Processing (Green Cluster)

One of the most critical areas is the data processing, i.e., green cluster (see Fig. 2). The imagery data with a high resolution collected using UAVs can be processed

Table 1 Occurrence of author keywords

Keywords	Links	Link strength	Occurrence	Average publications year	Average citations
Algorithm design and analysis	3	5	3	2019	0
Autonomous vehicles	4	4	3	2016	22
BIM	8	9	4	2017	25
Bridge inspection	5	6	3	2018	21
Cloud computing	8	9	6	2019	10
Collision avoidance	4	7	6	2016	9
Computer vision	13	22	10	2017	20
Control	6	17	12	2017	13
Convolutional neural networks	4	5	3	2019	2
Deep learning	7	16	8	2019	2
Deep neural network	3	4	3	2019	12
Detection	2	4	3	2019	2
Device-to-device (d2d)	2	4	3	2019	14
Disaster management	3	3	3	2018	2
Distributed robot systems	6	16	4	2017	16
Drone	63	195	298	2017	10
Edge computing	6	9	6	2019	3
Energy consumption	4	6	5	2019	2
Energy efficiency	2	5	6	2018	5
Energy management	3	4	3	2017	8
Fanet	6	11	6	2019	10
Fault tolerant control	2	4	4	2016	6
Flight control	2	3	3	2013	11
Formation control	3	6	5	2017	11
Fuzzy logic	2	5	4	2017	6
GPS receiver	3	7	3	2020	1
Image processing	7	10	7	2017	14

(continued)

Table 1 (continued)

Keywords	Links	Link strength	Occurrence	Average publications year	Average citations
Inspection	8	10	3	2019	11
IoT	15	24	14	2019	9
Localization	3	4	3	2019	1
Machine learning	11	15	7	2019	13
Mobile robots	8	18	5	2017	13
Mobility	7	8	3	2017	12
Multi-agent systems	4	4	3	2016	10
Multi-robot coordination	6	15	3	2016	21
Navigation	6	9	5	2016	15
Obstacle avoidance	7	10	5	2017	12
Omnibusf4v3	3	7	3	2020	1
Optimization	3	6	4	2019	0
Particle swarm optimization	5	8	6	2017	34
Path planning	10	17	14	2017	16
Photogrammetry	6	10	7	2017	69
Point cloud	5	7	3	2017	19
Pose estimation	3	5	3	2018	4
Positioning	2	3	3	2019	0
Privacy	6	8	3	2018	3
Remote sensing	5	7	4	2018	1
Remotely operated vehicles	6	15	3	2016	21
Remotely piloted aircraft systems	2	4	4	2018	14
Routing	3	4	3	2016	33
Routing protocols	5	8	3	2018	18
Safety	7	11	9	2017	3
Safety case	2	5	3	2017	19
Security	13	17	5	2018	5
Self-organization	3	4	3	2018	7
Simulation	8	12	7	2017	9
Smart city	6	7	3	2019	3
Stm32f405	3	7	3	2020	1

(continued)

Table 1 (continued)

Keywords	Links	Link strength	Occurrence	Average publications year	Average citations
Trajectory planning	2	4	3	2016	26
UGV	5	8	4	2018	5
Visual inspection	4	6	3	2019	5
Visual navigation	6	11	3	2017	12
Visual tracking	3	3	4	2017	3
Wireless communication	3	4	4	2019	4
Wireless sensor network	5	9	5	2018	1

using machine learning [16]. As shown in Table 1, the average publication year for "Machine learning" is 2019, showing its popularity in the past two years. As such, such keywords as convolutional neural networks, deep neural network, point cloud, computer vision, photogrammetry, building information modeling (BIM), navigation, remote sensing, deep learning, and visual tracking appear in this cluster. Several studies explored the use of UAVs for visual monitoring in the AEC/FM industries. As remote sensing, the application of UAVs has been studied with the average of the publication year of 2018. The use of BIM technology with drones has a significant value of research that is being studied in order to achieve the compression between as planned as built. For instance, Qu et al. [15] integrated BIM technology with UAV to monitor the construction work progress. Since the BIM provides as-planned data and UAVs collect as-built data. Another example for the use of UAV with BIM, is the automatic monitoring of construction progress through the implementation of UAV and 4D BIM [5]. Also, Liu et al. [9] proposed a safety inspection process by integrating UAV with dynamic BIM to identify hazards. The Keyword BIM appears in the research with the average year of 2017. The data collected by UAV, such as images and videos, can be processed and analyzed using the image processing technique. For example, Ellenberg et al. [2] proposed the use of UAV with image processing for the inspection of bridge structure damages. The proposed approach was tested and identified the structural cracks in lab experiments. Image processing appears with the average publication year of 2017, as shown in Table 1.

3.1.4 IoT (Blue Cluster)

Internet of things (IoT) is the emerging technology that is crucial in the smart use of new technologies. The research of applying UAVs in the field of AEC/FM has used the keyword of IoT with an occurrence of 14 with an average publication year of 2019. The use of IoT on operating the drone is valuable. For example, Kim and

Ben-Othman [8] proposed a surveillance model that avoids collision for a multi-domain IoT environment using smart UAV. McCabe et al. [13] suggested further research for IoT-based UAVs since the integration brings the opportunity to enable intelligent monitoring of the construction and facility. Another keyword in this cluster is localization, with an occurrence of 3 and an average publication year of 2019. In addition, the keywords of energy consumption and energy efficiency were used in the research of UAV-based AEC/FM applications with the average publication year of 2019 and 2018. Moreover, the keyword trajectory planning appears in the literature with an occurrence of 3 and the average publication year of 2016. Furthermore, the keyword device-to-device (d2d) was found in the cluster with an occurrence of 3 and an average publication year of 2019.

3.2 Citation Analysis

The citation analysis for the selected documents has been performed to identify significant publications in the area of UAV for the AEC/FM industry. In the VOSviewer, the minimum number of citations was set at 30 and resulted in 57 publications. The highest-cited 15 documents are provided in Table 2. The classification of the highest cited papers is as follows: (1) numbers 2, 6, and 12 in Table 2 on control (i.e., Group 1) and (2) numbers 8 and 14 in Table 2 on the outdoor and indoor environment (i.e., Group 1). Furthermore, papers (Number 5 and 10 in Table 2) are related to wireless communication and drone communications (i.e., Group 1). Number 15 in Table 2 is about the data collection (i.e., Group 3). It is clear that the research in UAV applications in the AEC/FM industry has been highlighted in these two groups. Another significant publication (Number 7 in Table 2) is related to the IoT (i.e., Group 4). It clarifies the advantages of drone applications. Furthermore, Number 9 in Table 2 is on collision avoidance that is an essential area of research for UAV operations (i.e., Group 1).

4 Discussion

The keywords co-occurrence analysis using VOSviewer identified the research trends of the UAV applications in the AEC/FM industry and classified them into four clusters, including (1) path planning/collision avoidance, (2) safety, (3) data and data processing, and (4) IoT. These four clusters mainly focus on the optimal flight path planning, flight control, avoid collision, the coordination of multi-robot, the distributed robot systems, wireless communication, drone safety, the privacy concern, security, routing protocols, navigation, data collection, processing data through machine learning, localization, IoT, and energy management. As indicated in Fig. 1 and Table 2, Group one and Group three have the most attention from scholars in UAV applications in the AEC/FM industry. Even with this, UAV path planning for

Table 2 Most cited documents related to UAV applications in the AEC/FM industry

Number	Document	Title
1	Siebert s. (2014)	Mobile 3D mapping for surveying earthwork projects using an Unmanned Aerial Vehicle (UAV) system
2	Maza i. (2010)	Multi-UAV cooperation and control for load transportation and deployment
3	Lu h. (2018)	Motor anomaly detection for unmanned aerial vehicles using reinforcement learning
4	Cesetti a. (2010)	A Vision-based guidance system for UAV navigation and safe landing using natural landmarks
5	Li b. (2019)	UAV communications for 5G and beyond: Recent advances and future trends
6	Kendoul f. (2010)	Guidance and nonlinear control system for autonomous flight of minirotorcraft unmanned aerial vehicles
7	Gharibi m. (2016)	Internet of Drones
8	Chowdhary g. (2013)	GPS-denied indoor and outdoor monocular vision aided navigation and control of unmanned aircraft
9	Lai j. (2011)	Airborne vision-based collision-detection system
10	Tuna g. (2014)	Unmanned aerial vehicle-aided communications system for disaster recovery
11	Zhang c. (2012)	An unmanned aerial vehicle-based imaging system for 3D measurement of unpaved road surface distresses
12	Rinaldi f. (2013)	Linear quadratic control for quadrotors UAVs dynamics and formation flight
13	Han j. (2013)	Low-cost multi-UAV technologies for contour mapping of nuclear radiation field
14	Benini a. (2013)	An IMU/UWB/vision-based extended kalman filter for mini-UAV localization in indoor environment using 802.15.4a wireless sensor network
15	Jawhar i. (2014)	A framework for using unmanned aerial vehicles for data collection in linear wireless sensor networks

indoor inspection is still a challenge. Along with the indoor inspection, GPS receivers for indoor inspection (GPS receiver with the occurrence of 3, the average publication year of 2020, and the average of citation 1 as shown in Table 1) demand more investigation. Safety and privacy are important aspects to consider in further research since people are concerned about protecting their privacy.

Moreover, the keyword privacy appears with an occurrence of 3, the average publication year of 2018, and average citation of 3 as shown in Table 1. In addition, drone and data processing is a significant area that is being studied by scholars to identify data processing techniques to analyze the data such as images and video (image processing keyword with the occurrence of 7, the average publication year of 2017, and average citation of 14 as shown in Table 1). Another important area that has the potential to facilitate the inspection process using UAVs in the AEC/FM field is BIM technology. It is because BIM allows the collection of geometric data as planned to match-up and differentiate with actual implementation in the site (BIM keyword with the occurrence of 4, average of the publication year of 2017, and the average of citation of 25 as shown in Table 1). Lastly, one crucial area is IoT, and identified as cluster 4 has a significant role in the UAV's operation, such as smart operation and localization. The keyword of IoT has an average citation of 9, as shown in Table 1.

5 Conclusion and Future Work

This paper aims to identify the state of the art of research for UAV applications in the AEC/FM industry. VOSviewer has been applied to conduct a bibliometric analysis in the area of UAV application in the AEC/FM industry based on the literature for the last ten years (from 2010 to 2020) retrieved from Scopus. The bibliometric analysis is presented in the form of the co-occurrence of the author keywords and citation analysis. The results include the research trends of UAV applications for the AEC/FM industry, challenges of the UAV applications, and future research directions. Furthermore, the research needs are as follows: (1) indoor path planning, (2) drone limitations such as batteries, (3) the integration between BIM and UAV, (4) privacy concern and (5) the integration of UAV-IoT for smart operation. This paper contributes to the body of knowledge by (1) quantitatively analyzing the research trends related to drone UAV for AEC/FM applications, (2) identifying research needs and future direction through the discussion of research clusters. Further research, including mixed types of analysis such as quantitative and qualitative for UAV applications in the AEC/FM industry, will be applied in future research.

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Scheduling Annual Inspections of Sanitary Trunk Sewers Using a Prioritization Framework

Khalid Kaddoura, Nicholas Gan, and Leo Chen

1 Introduction

Sewers are an essential asset for any community [1, 4]; it is considered a core asset as per the Government of Canada [3] and US Homeland Security Department [7]. Their main service is to transfer sewers safely to wastewater treatment plants or any disposal areas. Generally, these assets are subject to deterioration due to external (i.e. soil condition) and internal factors (i.e. sewage material). These assets, if not well managed, will deteriorate and eventually cause major consequences upon failure [6]. Therefore, it is essential to properly plan and manage these assets during their service lives [2].

Condition assessment is one of the primary steps utilized prior to performing maintenance, rehabilitation, or replacement activities. In sewers, the most commonly used inspection technique is the closed-circuit television (CCTV). The results from this inspection are used to evaluate the internal condition of the pipeline to determine the structural and operational states.

In partnership with Water Research centre (WRc) and to establish a database for the North American market, the North American Sewer Service Companies (NASSCO) developed the Pipeline Assessment Certification Program (PACP), which is a standard utilized by municipalities across Canada and the United States (US) [5]. In PACP, each defect is assigned a code, where each defect code has a specific condition grade ranging from 1 to 5.

Condition grades are one of the main inputs to any risk management framework along with the consequence of failure. Incorporating both parameters will aid in

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S. Walbridge et al. (eds.), *Proceedings of the Canadian Society of Civil Engineering Annual Conference 2021*, Lecture Notes in Civil Engineering 247,
https://doi.org/10.1007/978-981-19-0968-9_21

prioritizing assets for inspections and/or rehabilitation and maintenance. Ultimately, the main goal is to avoid major disruptions while keeping assets in an acceptable condition (depending on a threshold determined by a specific municipality).

The existing literature includes a variety of researches that developed prioritization models to tackle the planning issue in sewer networks. However, prioritization methodologies specific to trunks were not specifically identified. In addition, a detailed desktop analysis of the accessibility factor was rarely discussed and modelled. Thereby, the main aim of this paper is to present a methodology to prioritize trunk sewers based on an Importance Grade that accounts for the criticality and accessibility.

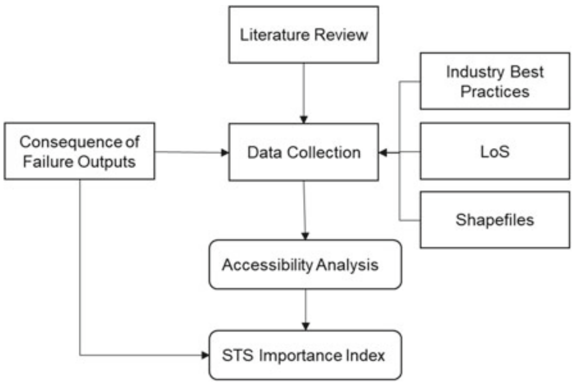
Once the Importance Grade is calculated for each STS segment, the corresponding vulnerability and ICG can be combined to determine an inspection frequency. This model can be utilized by cities and municipalities to plan for future interventions on their sewer networks.

2 Methodology

The methodology in this paper aims at discussing the development of an Importance Grade (Fig. 1), which was one of the overall tasks of the project. In summary, the project consisted of three main tasks:

1. Inventory review of Sanitary Trunk Sewers (STS) and their distance from floodplains and waterbodies.
2. Review of historical condition assessment using CCTV data as well as the development of multiple regression prediction models to predict uninspected STS and geoprocessing the STS data to develop an accessibility model.
3. Incorporate accessibility information, CCTV data and predicted grades, and vulnerabilities of each STS to prioritize assets.

Fig. 1 Methodology



3 Case Study

This paper implemented the models developed on the STS network for the Region of Peel in Canada. The Region is responsible for the operation and maintenance of the STS network, pumping stations, and wastewater treatment plants within the Regional Municipality of Peel boundaries. The Region implements a robust condition assessment and rehabilitation program but aims to enhance its existing practices through a reliable prioritization process.

Based on the inventory of the network, the majority of the STS segments were installed between 1967 and 1976 (Fig. 2). The total length of segments observed with a missing year of installation was roughly 1.7 km. The "Unknown" bin includes assets that have years of installation entries as "1/1/1900" and "1/1/9999". Approximately 175 km of the STS ranged between 750 and 1050 mm. This range dominated the sizes of the STS by length (Fig. 3). Roughly 18 km of STS have diameters greater than 1950 mm. Concrete STS dominate the material types with a total length of approximately 244 km. The second most governing material is the Reinforced Concrete STS, with a total length of 46 km (Fig. 4).

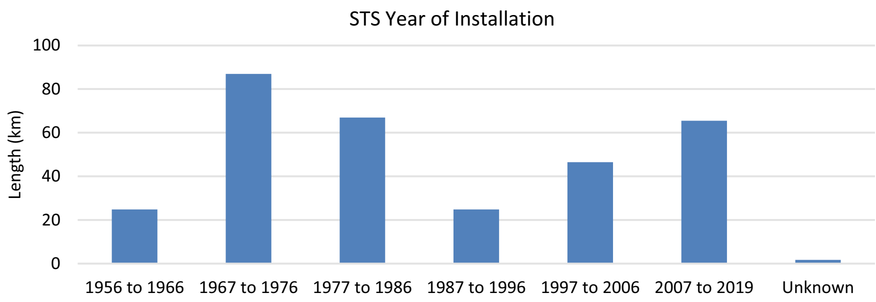


Fig. 2 Installation by length

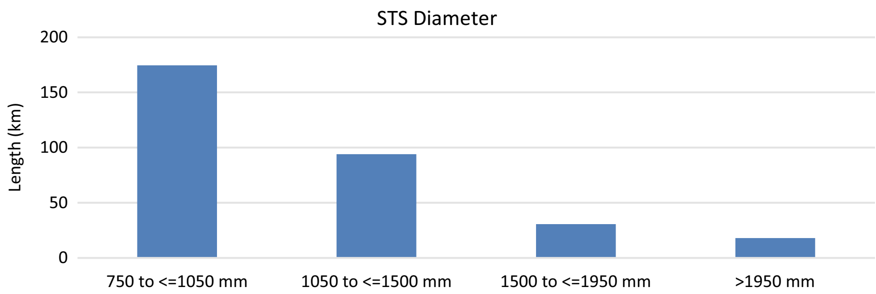


Fig. 3 Diameter by length

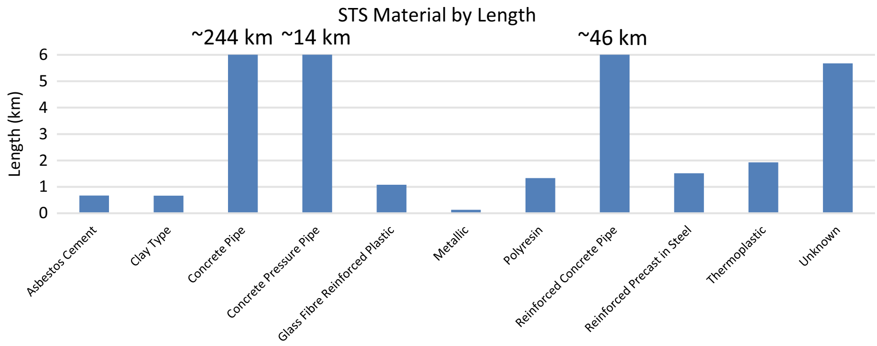


Fig. 4 Material by length

Table 1 CoF scores

Category	Scores
Negligible	1
Low	2
Moderate	3
Severe	4
Catastrophic	5

Within the geodatabase, the CoF results were also available which were used to calculate the overall Importance Grade. The CoF criteria were based on the impacts of:

- Structural Failure;
- Capacity; and
- Blockages.

Each criterion consisted of scores ranging from 1 to 5. The scores were defined as per Table 1.

4 Model Development

4.1 Accessibility

An understanding of the pipeline accessibility considerations for operations, maintenance, rehabilitation, or replacement (interventions) is essential for enhanced planning and management activities. Theoretically, the determination of accessibility level relies on multiple factors to distinguish accessible and inaccessible pipelines.

Generally, accessible pipelines have a higher probability to be selected for interventions when compared to inaccessible sewers. The latter requires significant planning, communication, coordination activities between different communication channels prior to any maintenance activities. As part of the planning, considering intervention actions for inaccessible sewers may require enabling work requirements which would increase the overall intervention costs. Given these circumstances, some of these pipelines may dominate the backlog of any financial planning.

Overlooking these types of assets decreases the opportunity of monitoring their deterioration behaviour. Increased risks will further be associated with larger diameter pipelines that, in case they collapse, would have significant failure consequences in terms of the economy, environment, operation, and society. Therefore, sewer networks that are managed considering risk-based approaches consider accessibility to highlight their significance for budget planning. Overall, studying the accessibility of sewers:

- Determine the required level of communication and planning activities prior to any intervention
- Assist in the budget allocation needed for accessible and inaccessible sewers
- Align with the Region's Levels of Service (LoS) performance measures requirements for managing STS
- Increase attribute definition of STS in a geodatabase
- Enhance risk-based application for better prioritization conclusions.

The accessibility study conducted in this assignment was a desktop-based model that relied on available attribute data of STS to differentiate the accessibility levels of existing assets according to High, Moderate, and Low. Table 2 shows the accessibility factors and definitions.

Ultimately, prioritization, scheduling and optimized budget allocation problems are mostly focused on activities critical to ensure sustainable performance of the assets. The accessibility factors included parameters related to STS proximity to water bodies, environmentally sensitive areas, among others which are found in Table 2. While these parameters increase the overall criticality of any asset, as per the Environmental Protection Agency (EPA)'s maintenance practices, scheduling is a major component of the overall process. Determining the annual inspection based on prioritization is relevant to a scheduling problem. For any schedule considering a finish to start activities (a typical relationship in sewer inspection), successors that are expected to be delayed due to a longer duration of a predecessor are prioritized for optimized scheduling; in scheduling, these are called "long-lead" items/activities.

Assets with lower accessibility would most likely require civil/mechanical enabling work, communication between different stakeholders, traffic arrangement needs, etc. Therefore, they need additional time for preparation compared to higher accessibility assets; they need to be given an additional degree of focus to add another layer of prioritization.

Since the accessibility is based on multiple factors, combining the contribution of each factor on the accessibility level is necessary. Therefore, the accessibility was determined by deploying a weighted average method, where each factor has a

Table 2 Accessibility factors

ID	Factor	Definition
1	Watercourse	This factor determines the distance of the STS closest to a watercourse. STS that are closer to watercourses will have a decreased accessibility levels
2	Rail road crossing	This factor is based on binary data. STS that crosses railroads will have a decreased accessibility levels
3	Easement	This factor determines whether the STS is located within an easement or not. STS that are within an easement would have decreased planning requirements when compared to STS that are outside the easement. Therefore, STS within an easement will have a higher accessibility level
4	Floodplain	This factor determines whether the STS is located within a floodplain or not. STS that is within a floodplain will have a higher probability of flood events. STS within these locations would have decreased accessibility levels (this is based on the worst-case in which STS requires maintenance while the location is flooded)
5	Bridge and culvert proximity	This factor determines the distance of the STS to the closes bridge or culvert. STS that are closer to bridges or culverts will have decreased accessibility levels
6	Woodland Provincial park Toronto and region conservation authority (TRCA) Credit valley conservation (CVC)	This factor determines whether an STS is located in woodland, provincial park, TRCA area, and CVC area. STS that is within any of these areas will require significant coordination and planning level
7	Land use	This factor determines the type of land an STS is located in. Vacant lands will have higher accessibility levels than commercial areas
8	Street class	This factor determines the class of a street an STS is located in. Streets with higher Average Annual Daily Traffic (AADT) is expected to have lower accessibility levels

specific relative importance weight (refer to Eq. 1).

$$Accessibility = \sum_{i=1}^{8} W_i AV_i \quad (1)$$

where W_i is the relative importance weight of each factor; AV_i is the attribute value of each factor. The attribute value ranges between 1 (low accessibility level) and 10 (higher accessibility level) (refer to Table 3).

Based on the relative importance weights and attribute values, Eq. 1 supplies a grade that ranges between 1 and 10. As per the definition of the attribute values, grades that are closer to 1 represent low accessibility levels and grades that are closer

Table 3 Accessibility factors attribute values

ID	W (%)	Factor	Attribute	Attribute value (AV)
1	25	Watercourse	Up to 5 m	1
			5–30	5
			>30	10
2	10	Railroad crossing	Yes	1
			No	10
3	5	Easement	Yes	10
			No	1
4	25	Floodplain	Yes	1
			No	10
5	10	Bridge and culvert proximity	Up to 5 m	1
			5–30	5
			>30	10
6	15	Woodland Provincial park Toronto and region conservation authority (TRCA) Credit valley conservation (CVC)	Yes	1
			No	10
7	5	Land use	Agricultural	10
			Commercial	5
			Government	1
			Industrial	1
			Institutional	1
			Residential	5
			Special purpose	1
			Vacant	10
8	5	Street class	Local road—Major	5
			Local road—Minor	10
			Provincial freeway	1
			Ramp	1
			Regional road	1

Table 4 Accessibility rate and grade

Accessibility rate	Lower breakpoint	Higher breakpoint
High	>7	10
Moderate	>4	7
Low	1–4	4

to 10 indicate higher accessibility levels. Similarly, a computed accessibility grade that is closer to 1 represents a low accessibility level, and a grade that is closer to 10 represents a higher accessibility level.

These grades are divided into qualitative ratings based on three-point definitions, and the breakpoints are shown in Table 4. For instance, an STS that has an accessibility grade of 4.5 is defined in the Moderate category.

4.2 STS Importance Grade

The STS Importance Grade accounts for a detailed desktop accessibility analysis and considers the CoF study supplied by the Region. Each score, from the accessibility analysis and CoF, are aggregated using relative importance weights. Considering the equivalent importance of the CoF and accessibility, each score is assigned a relative importance weight of 50%. Hence, the contribution of the CoF and accessibility scores is similar. The scores of 1–10 assigned for the accessibility are linearly converted so that higher scores would represent lower accessibility while lower scores would refer to higher accessibility. Therefore, the CoF and accessibility scores are consistent once applied. Any aggregation of the two scores will provide an overall indication to prioritize STS; an aggregated score closer to 10 would reflect an increased priority of the analyzed STS.

The STS Importance Grade can be calculated as follows:

$$STS\ Importance\ Grade = 0.5 \times CoF + 0.5 \times Accessibilty \tag{2}$$

The calculated grades can be converted to categories as per Table 5.

Table 5 STS importance grade breakpoints

STS importance category	Breakpoints
Low	1–4
Moderate	4–7
High	7 and greater

5 Results

The accessibility ratings are divided into three categories: High, Moderate and Low. Based on the set of criteria, attribute values, and relative importance weights, an accessibility grade was computed. From Fig. 5, the Low and Moderate category share almost the same length of STS with a value of 251 km. This length corresponds to approximately 79% of the STS inventory. From the same figure, 66 km of the STS segments rated as Low accessible assets. Further, all three accessibility ratings were observed in all diameter ranges. The greatest total length of Low accessible STS was observed in the diameter range between 750 and 1050 mm with a length of 27 km; however, the share of this length to the total length was the lowest when compared with other diameter ranges. The highest percentage of the Low accessible STS was observed in larger diameters (greater than 1500 mm).

When combing the CoF scores with the accessibility scores, the STS Importance Grade was computed. As per Fig. 6, more than half of the STS were in the Moderate to High. Since the STS Importance Grade accounted for the accessibility parameter,

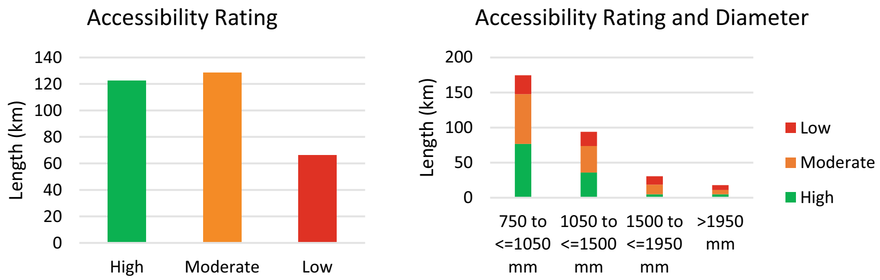


Fig. 5 Accessibility ratings by length

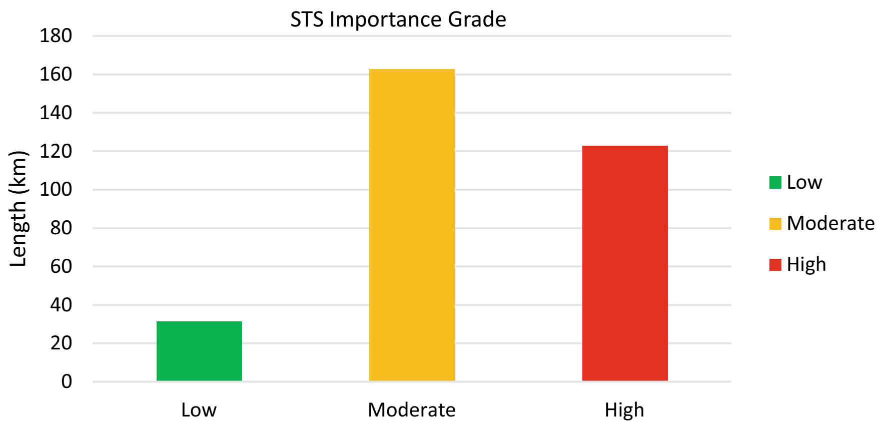


Fig. 6 STS importance grade

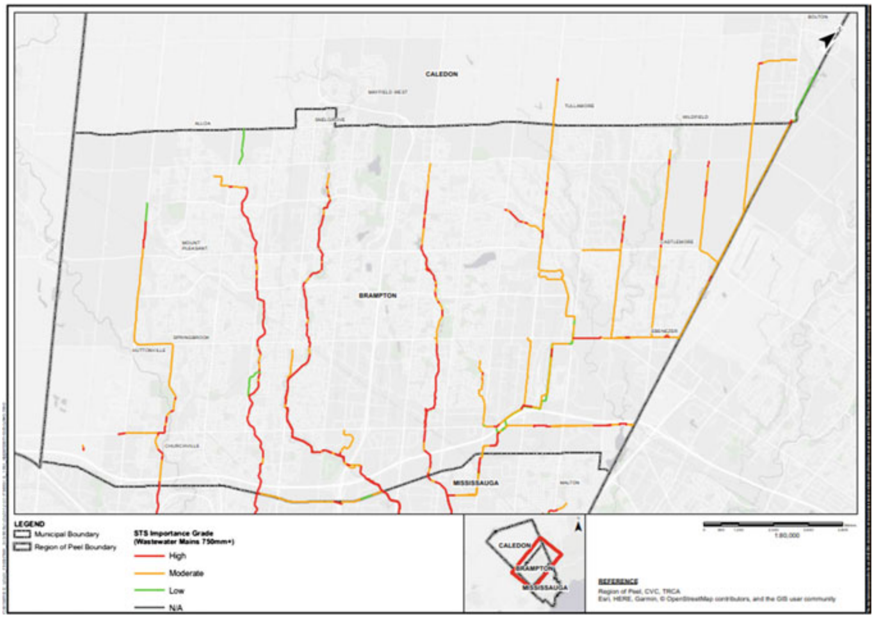


Fig. 7 STS in Brampton

the floodplain and proximity to water bodies were considered in the prioritization scheme. Based on the prioritization and from the identified STS that would be scheduled for inspection in the next five years, 84% (136 km out of 162 km) of the observed STS were within a floodplain and 87% (83 km out of 95 km) of the STS were within a 10 m distance of the closest water body. The total length of STS segments that were within a 10 m distance of water bodies and were within a floodplain identified for an inspection within the five-years was 76 km (96% of the total length of STS that were within a floodplain and within 10 m distance of a water body). Geographic Information System (GIS) maps are generated to display the segments by their STS Importance Grade category (Figs. 7 and 8).

6 Conclusions

Planning and management of trunk sewers are essential to limit risk exposures. In an effort to enhance existing practices utilized at the Region of Peel, a methodology was developed to prioritize STS at a close proximity to floodplains and water bodies for inspection. The presented methodology relied on data collected from the Region, including shapefiles and existing CoF results. The Importance Grade for each STS was calculated through the weighted average method by considering the scores of the accessibility and CoF. The accessibility considered eight different parameters,

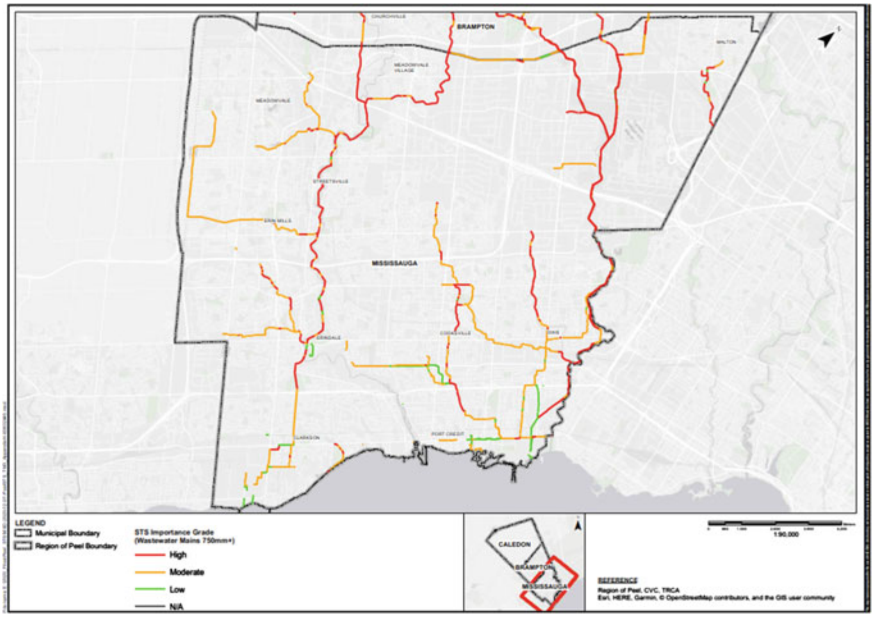


Fig. 8 STS in Mississauga

including proximity to watercourses, railroad crossing, easement, proximity to floodplain, proximity to bridge and culvert, environmentally sensitive areas, land use, and street class. The accessibility and STS Importance Grade ranged between 1 and 10, where grades closer to 10 have higher importance. The total length of STS segments that were within a 10 m distance of water bodies and were within a floodplain identified for an inspection within the five-years was 76 km (96% of the total length of STS that are within a floodplain and within 10 m distance of a water body). Based on the findings and by incorporating the vulnerability, ICGs and STS Importance Grades, the Region will most likely be inspecting 36 km of STS segments per year in the next five years.

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Use of Virtual Reality to Minimize the Spread of Covid-19 on Construction Sites

Allison Boyd, D. Cody Bradley, and Lloyd M. Waugh

1 Introduction

In 2004 the University of New Brunswick (UNB) began preliminary work on a virtual reality documentation (VR Doc) system to document construction progress. The first ongoing VR Doc system [1] was developed in 2006 for the New Brunswick Department of Supply and Services on the Hartland School project [2]. A variety of projects have been completed since then, including documentation of: the Point Lepreau Nuclear Generating Station Refurbishment for NB Power Corporation, the One Mile House Interchange for the New Brunswick Department of Transportation, and the New Brunswick Law Courts jointly for Bird Construction Inc. and the New Brunswick Department of Supply and Services. Some of the major improvements to VR Doc since its introduction include faster processing, the ability to use VR Doc on both Mac and Windows software, a faster and more user-friendly interface, and overall quality improvements. Historically, VR Doc had four purposes (a) virtual site visits, (b) photographic as-builts, (c) pre-emptive delay claim resolution, and (d) training junior project managers. This paper applies the virtual site visit capabilities of VR Doc in reaction to COVID-19.

The COVID-19 pandemic created many challenges for the New Brunswick construction industry. Beginning in mid-March 2020, New Brunswick Public Health put in place a tiered recovery plan with various levels of restrictions depending on the impact of the virus. There are four levels in New Brunswick: green, yellow, orange, and red. Information regarding the levels and their associated restrictions are found on the Government of New Brunswick (GNB) website (note that the restrictions for

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S. Walbridge et al. (eds.), *Proceedings of the Canadian Society of Civil Engineering Annual Conference 2021*, Lecture Notes in Civil Engineering 247,
https://doi.org/10.1007/978-981-19-0968-9_22

each level have evolved over time). Information from Public Health and the province is communicated via livestreamed conferences. The red level has the highest restrictions and is intended to contain the virus as quickly as possible, while the other levels have decreasing restrictions until the green phase is reached and herd immunity has been achieved [3].

The Canadian Construction Association (CCA) also introduced *COVID-19 Standardized Protocols for All Canadian Construction Sites* [4]. The protocols include preventative detection and response measures to be followed on construction sites across Canada. All personnel on New Brunswick construction sites must follow the COVID-19 prevention procedures as posted by the CCA and the New Brunswick Construction Safety Association (NBCSA) during red, orange and yellow levels, as well as the additional restrictions and regulations put in place by the government. Procedures include hygiene practices, social distancing measures, health verification procedures for workers, visitors, and others [5].

Pre-COVID-19 there was a free flow of tradespeople, subcontractor crews, inspectors, and project management personnel travelling to and from construction sites. To minimize the spread of COVID-19, projects have been operating under WorkSafeNB guidelines [6] as well as the above mentioned government regulations and CCA and NBCSA standardized protocols and procedures. The usual free flow of people from site-to-site is currently monitored and minimized as provincial levels change and project personnel work from home whenever possible. Inspection of the work by government agencies (to assess code/regulatory compliance for plumbing, heating, ventilation, electrical, etc.) and by consultants (to assess the scope and quality of the work) is halted due to the potential exposure of inspectors to COVID-19 as well as the risk that they would spread it to other sites. There are also restrictions in place during GNB's red, orange, and yellow restriction levels that do not allow people from out-of-province within provincial borders, and regulations that require people to self-isolate for 14 days upon entering or leaving the province. These regulations make it difficult or impossible for out-of-province project personnel to visit a construction site when needed.

2 Project Description

2.1 Project and Participants

The Fredericton International Airport has experienced significant passenger and job growth over the past six years. The original Air Terminal Building was built in the 1960s and its capacity had been expanded to 200,000 passengers annually. In 2018, the airport saw approximately 423,000 passengers. The current expansion project will increase capacity to 500,000 passengers per year, has a total cost of $30 million dollars, and began construction in May 2019 [7]. Bird Construction is the general contractor for the airport upgrade project and have provided access to the site to implement VR Doc over a five month period. Personnel participating in this research project include representatives of the project owner, the general contractor, and the electrical subcontractor. Each party gave feedback throughout the project, providing insight as to the value of using VR Doc during a pandemic, in particular its ability to reduce site visits thus minimizing the spread of the virus.

Eighteen locations were established in consultation with the project participants in order to best capture construction progress. When viewed on the VR Doc website, the locations form a relatively comprehensive virtual reality walkthrough of the site and include key areas both inside and outside of the building. The number and choice of panorama locations are determined in an attempt to emulate a physical walk-through of the project. Our theory is that there is a limit to the number of virtual panoramas that a virtual visitor will view, just as there is a limit to how many rooms a person physically walking through the site will view. An additional guiding principle is that we want to choose panorama locations that provide a broad or unique perspective, for example intersections of hallways or a particular type of room (e.g. an office or a waiting room).

The panorama locations are presented on a site plan of the airport upgrade in Fig. 1. Note that the areas of the building without panoramas are areas of the airport that had minimal or no renovation.

Four additional panorama locations were added in the major electrical rooms midway through the five-month study period to provide the electrical subcontractor with a better view of the circuit breakers. A visual view of the breakers in the electrical panel is a measure of completed work and therefore be used to monitor progress.

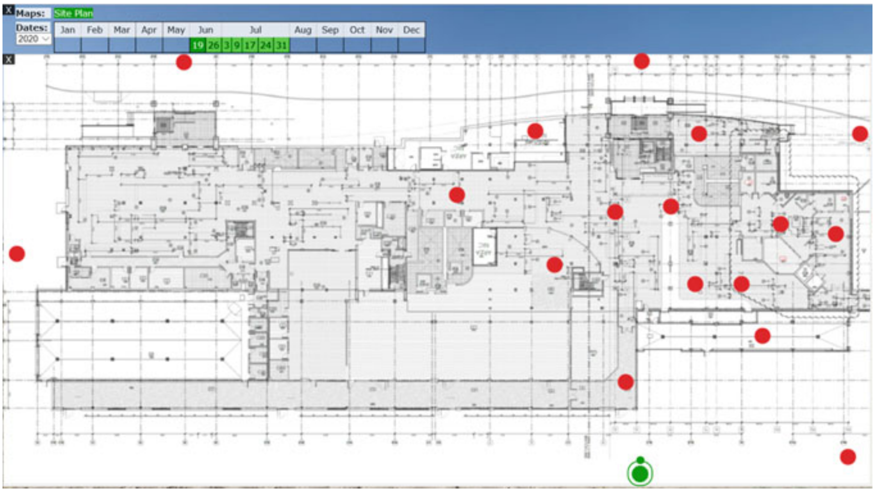

Fig. 1 VR Doc Map with panorama locations

2.2 *Panorama Capture and Processing*

Panoramas were captured on a weekly basis on Fridays from June 2020 to November 2020. Fridays were chosen as there were fewer workers on site thus minimizing COVID-19 risks and potential blur in the images due to personnel and equipment movement. The previously developed image capture and image processing methods were followed [8]. The standardized process ensures high quality imagery is captured efficiently and also enables the use of batch processing tools for further efficiency.

3 VR DOC Interface

The VR Doc interface has previously been described by Bradley et al. [8]. The following is an overview. The interface serves as a storage, organization, visualization and delivery tool. The panoramas are stored on a server and allow the client access without permanently downloading the panoramas. Organization is achieved through a series of Maps and Dates that allow a user to select a panorama from a specific Map and Date of interest. The selected panorama is visualized within the web-based interface and delivered over the internet. Figure 2 presents a view of the airport upgrade project in the VR Doc interface. The site plan is minimized so the panorama can be viewed without obstruction. The date selected from the Site Plan Map is September 11, 2020, as indicated by the dark green boxes, and also the breadcrumb in the upper right hand corner of the interface. The user can pan 360° as well as zoom in and out. A key advantage of high-resolution panoramas over still images is the

Fig. 2 Panorama of location 13

Fig. 3 Panorama location 13 ceiling detail

360° coverage that provides a comprehensive view from each panorama location—thus avoiding the need for site personnel to select site features of interest and then brief the photographer prior to each site visit.

Figure 3 panorama highlights the ability to capture and document elements of construction that are not visible once construction is complete. This panorama presents a zoomed in view of the electrical components and illustrates the level of detail captured.

The five-month study period provided a sufficient amount of time for significant construction progress to be made, thus providing users with access to the state of construction over longer time periods. It was anticipated that this would be valuable to those who were not able to visit the site on a regular basis. Figure 4 presents location 13 on two different dates: August 14, 2020 and October 2, 2020. In this mode, VR Doc applies all navigation actions to both panoramas to synchronize panning, zooming, etc.

4 Potential Benefit

A questionnaire was created and distributed to project participants to capture their feedback regarding use of VR Doc as a tool to minimize the spread of COVID-19 on site. This included representatives of the project owner, general contractor, and electrical subcontractor with a combined total of 44 years in the construction industry. The questionnaire responses have been categorized in the following sections for clarity and therefore represent our interpretation of the feedback received.

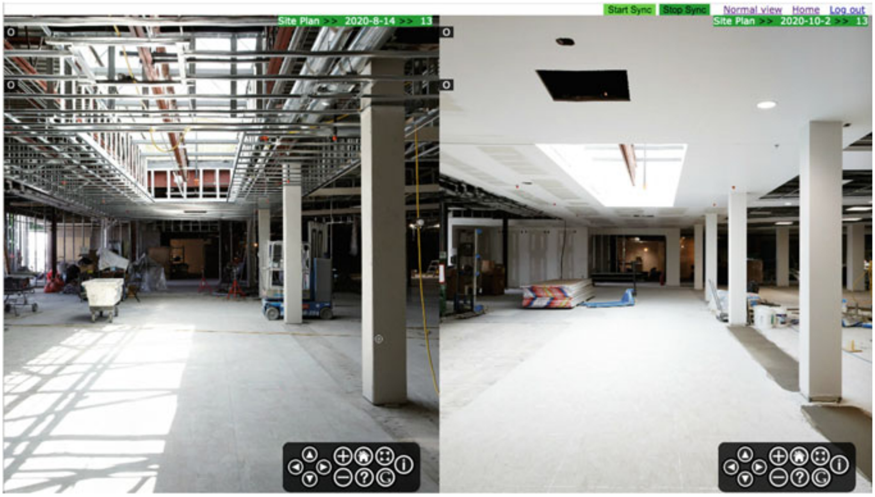

Fig. 4 Panorama location 13 at two different dates

4.1 Changes to Normal Site Procedures Due to COVID-19

Due to COVID-19, usual site operations have been changed due to new regulations to minimize spread of the virus. Following the protocols and regulations described in the Introduction, all site personnel must undergo daily temperature checks and answer a COVID-19 questionnaire every day prior to working on site. For trades, all workers must maintain physical distancing or have approved measures in place if physical distancing is not possible. COVID-19 has also limited the number of people who can come to site. For subcontractors, project management personnel make less frequent site visits to monitor the progress of their workers. Contractors, consultants and inspectors from within and outside of New Brunswick have had to delay or restrict their site visits, depending on the state of the province in terms of COVID-19 restrictions and the current COVID-19 level for the province.

4.2 Uses of VR Doc to Minimize Virus Spread

The representative of the project owner sees VR Doc as a useful tool for progress updates and as a means of providing visual information to members of the Fredericton International Airport Authority Board of Directors in meetings when discussing progress and project issues. VR Doc can be used as a visual aid in these meetings in place of a group site visit, minimizing the risk of spreading COVID-19. Additionally, the general contractor representative sees similar benefit for office-based project managers and upper management of the contractor through progress updates via VR

Doc, minimizing the need for site visits. These updates may also help trades' management personnel complete progress billings and progress updates from a remote location. The general contractor's representative, however, does not see VR Doc reducing the amount of time on site for those who are actively involved in the project (trades, subcontractors, general labourers, site managers, etc.) as their work on site cannot be replaced.

4.3 Other Useful Technologies

Other technologies used by the project representatives to address COVID-19 related challenges include virtual meeting software such as Zoom [9] and Microsoft Teams [10]. These both have a share screen option in which project personnel could use VR Doc as a visual tool in their meetings. Additionally, Procore, a software that allows all project personnel to share project plans and documents is also used for the project. Procore does have a feature to share photos and is used to share still images of general progress or specific project details to work with remotely. VR Doc provides more regular and consistent updates of site progress in the form of 360° panoramas.

4.4 Other Benefits of Using VR Doc

Both the general contractor and project owner representatives hypothesized a benefit of VR Doc being in the post-project phase. Both suggested VR Doc will be useful while undergoing maintenance and asset management. VR Doc shows factual photographic as-built conditions, providing information on locations, and the rough installation date of different systems that are hidden or buried after project completion. The high-resolution zoom feature in VR Doc, shown in Fig. 3, can also show precise locations and material types. This would allow future project operations personnel to find the information required to replace, repair, or refurbish assets without assistance from former project personnel.

4.5 Impediments to VR Doc Use

Feedback on impediments and potential improvements to VR Doc were also provided. The project owner's representative suggested panoramas be captured more frequently during busier project phases. A fixed weekly capture schedule is not always aligned to best capture critical site activities. Similarly, the electrical subcontractor's representative noted that the photographer would have to be on site at a scheduled time to capture electrical work as it is difficult to gage progress without a visual of the detailed work. This feedback suggests that a variable panorama capture schedule would be useful and would require close contact with site personnel to determine the capture schedule. A more frequent fixed schedule, such as every other day, could be considered, although the additional effort and increased time on site and therefore COVID-19 risk would have to be assessed. Other potential impediments include the introduction of yet another software interface, justifying costs of using VR Doc, and potentially missing small details that may be seen from a visit to site.

5 Conclusions and Recommendations

Many project participants, such as inspectors and consulting engineers, are unable to visit construction sites as often as they would like due to COVID-19 regulations. These regulations are constantly changing and it can be difficult to predict whether a site visit can be performed at a particular phase during the project, especially for out of province personnel and personnel who are within a different recovery level than that of the site. Feedback from project personnel suggests that virtual reality tools, such as VR Doc, could be helpful to those who are unable to come to site by allowing them to perform their tasks remotely. The risk of spreading COVID-19 may be reduced as a result, thereby having fewer people travelling from site to site and fewer people on site.

In New Brunswick, COVID-19 case numbers have been relatively low in comparison to other Canadian provinces. Red level restrictions were rarely required during the study period and were only used in specific regions of the province for short time periods to quickly halt the spread of the virus. Travel within the province and access to construction sites could have been much more challenging if case numbers were higher. It is anticipated that the responses to the questionnaire could have been much different if the virus had been more prevalent in the province. Implementing VR Doc on a site with a greater impact from COVID-19 would provide additional insight into the benefits.

Impediments, in particular cost, need to be evaluated against the potential benefits of using the system. Benefits should be evaluated at all levels of project participants, from owner to subcontractor. This type of evaluation would highlight the various requirements of each group, such as panorama location, frequency and resolution, and identify new benefits. A system that provides value to all project participants may justify integration with existing project management software, such as Procore, further facilitating delivery of and use of the system.

Acknowledgements We are grateful for the support and funding we have received from the New Brunswick Innovation Foundation (NBIF) as well as the assistance we received from J. Sorenson at Bird Construction and R. Dobbelsteyn.

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Systematic Literature Review on the Combination of Digital Fabrication, BIM and Off-Site Manufacturing in Construction—A Research Road Map

Amirhossein Mehdipoor and Ivanka Iordanova

1 Introduction

According to the scientific literature, 98% of megaprojects in the construction sector suffer cost overruns of more than 30%. This is due to many reasons, the most important of which is issues with productivity [1]. According to their report, construction productivity has been flat for decades while over the same period, it has doubled in manufacturing. This finding is also supported by the Mackinsey Global Institute, which reported that the construction industry has very low average profit margins compared to other sectors such as manufacturing [2].

Digital fabrication and off-site manufacturing in construction have recently become a prominent domain as they are seen as a potential response to the problems experienced by the industry. However, there have been very limited studies in this domain that link off-site manufacturing in construction to the concept of design for manufacturing and assembly [3].

The adoption of digital technology would be a way to increase productivity in construction. However, it is reported that the majority of construction automation research is related to the actual fabrication phase, and very little research has been done to develop technology in construction [4]. According to the same authors, in Canada, hardly any research has been conducted on the application of automation and robotics in construction.

The development and implementation of automation technology in construction has been slow due to the unavailability of suitable automation technology as well as

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S. Walbridge et al. (eds.), *Proceedings of the Canadian Society of Civil Engineering Annual Conference 2021*, Lecture Notes in Civil Engineering 247,
https://doi.org/10.1007/978-981-19-0968-9_23

effective and economical engineering technology for large and mega-scale projects [5]. These technologies should be considered early, from the planning and design phases. Their integration within a BIM environment, connected to the IoT for real-time information, would make it possible to monitor the progress and performance of a project. This in turn could potentially improve overall productivity.

BIM facilitates a wide range of building activities, such as digital fabrication of different building components as well as building construction. It has been observed that BIM is helping to improve the performance of off-site manufacturing (OSM) projects through its integrated management and cooperative behavior [6]. The application of BIM in an OSC project can improve its efficiency. For example, the quality of the design in an OSC project can be improved by BIM-based generative design. In addition, efficiency in data sharing can be improved by cloud BIM-based data exchange [7].

The aim of this literature review is to study the most up-to-date practices combining digital fabrication, building information modelling (BIM), and off-site manufacturing in construction (OSM). In the most recent studies, the application of BIM for OSC has been studied mainly in relation to design, data sharing, robotics and 3D printing for OSC. However, since this research is the initial phase of a project to develop a decision support system for BIM and OSM, key articles that discuss the process of decision making in BIM and OSM have been included.

The objective of this work will be met by answering two research questions: (a) What are the current research topics and trends regarding digital fabrication, BIM, and OSM in construction? (b) What are the research gaps, needs, current activities, and opportunities for future research (research road map)? This literature review will contribute to the body of knowledge by providing in-depth discussions on the main trends in off-site construction and current research gaps, and providing recommendations for near-future directions in off-site manufacturing. It is a part of a larger research project to identify the key success factors to help improve construction efficiency through OSM.

2 Methodology

This study is the initial stage of a comprehensive research project related to the development of a BIM-enabled decision support system (BeDSS) for digital fabrication in off-site manufacturing (OSM). In order to define the research focus, current studies related to BIM and OSM were investigated. The methodological approach of this study is based on a systematic literature review (SLR), which combines qualitative and quantitative methods, namely, a quantitative review by bibliometric approach and a qualitative review.

Bibliometric mapping is an important technique that visualizes the structural and dynamic aspects of scientific research [8]. Eck and Waltman [8] developed VOSviewer, a program that displays large bibliometric maps in an efficient way. This program is able to display a bibliometric map of authors or journals based on co-citation data or a map of keywords based on co-occurrence data [8]. VOSviewer was utilized by Oraee et al. [9] to conduct a bibliometric analysis to research on the collaborations of BIM-based construction networks [9].

A bibliometric search of digital fabrication, BIM, and OSC was performed in Scopus, which was chosen as the search engine for this research. By reviewing previous studies such as [3, 4, 7, 9, 10], the initial keywords were selected and all associated journal papers published in English between 2010 and 2020 were chosen.

Scopus provides downloadable data that can be imported into VOSviewer to generate bibliometric maps, such as, a map of the network among publications [3].

Figure 1 shows the literature review analysis diagram on the application of BIM and digital fabrication in off-site manufacturing.

The diagram in Fig. 1, shows the initial OSM search, which was filtered by searching a BIM-related set of keywords within the initial search. The dataset will be used further on, during the discussion of the qualitative method. By searching BIM within the initial search results, OSM within BIM's initial result and excluding any duplication, conference proceeding, book chapter, and editorial letter, the total number of related enhanced articles filtered to 219.

These articles have been used for a qualitative analysis to achieve the objective of this research. The systematic approach, including abstract reading and main body skim-reading to exclude non-related articles, limited the total number of key articles to 41 journal papers.

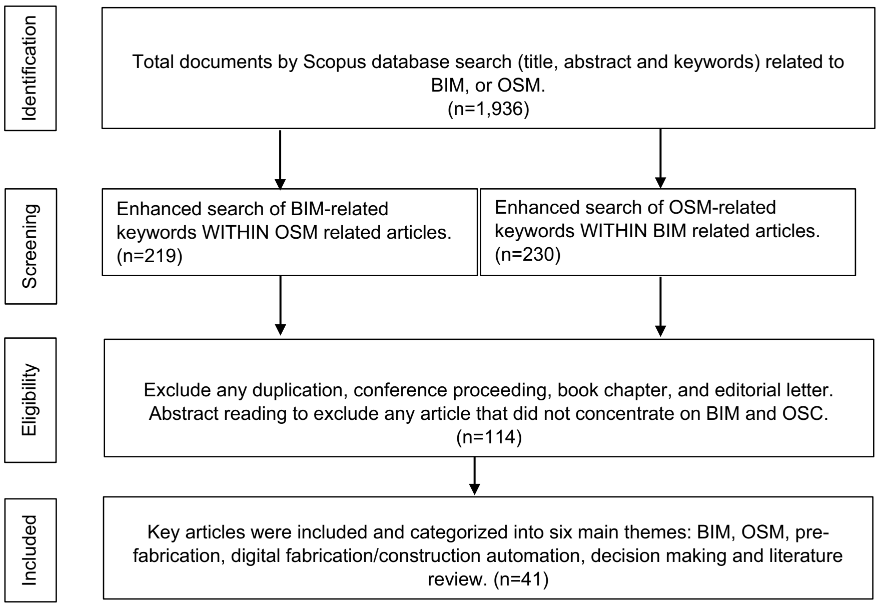

Fig. 1 Literature review analysis diagram

The articles were categorized into six themes, namely: BIM, OSM/OSC, Prefabrication, Digital Fabrication/Construction Automation, Decision Making, and Literature Review. Table 1 shows the summary of 41 key articles categorized based on these research themes.

3 Quantitative Analysis

To identify publications related to BIM, a search in Scopus for articles from the year 2010 to 2021 (until December 13, 2020), was conducted. The set of keywords used in this search was:

TITLE-ABS-KEY “BIM” OR (“Building Information Model”) OR (“Building Information Modelling”) OR (“VDC”) OR (“Virtual design and construction”).

The results of the above-mentioned initial search were then filtered to search OSM/OSC and Manufacturing within the BIM cluster. A total of 230 articles was selected as being the most related publications for further qualitative analysis. Figure 2 shows key journals related to OSM within BIM and the number of publications they had combining these two topics during the years 2010–2020.

To identify pioneer researchers in OSM within BIM, a bibliometric analysis was conducted and the key authors in OSM/OSC related to BIM were identified. The following Fig. 3 illustrates the result for authors with more than 5 publications in this domain.

The following keywords were used in a bibliometric search in Scopus, to identify the related articles published from 2009 to 2020 (up to December 8, 2020). All non-related subject areas were excluded, and the search was limited to English articles only. The set of keywords used for the initial search is as follows:

TITLE-ABS-KEY(“Off-Site Construction”) OR (“Off site Construction”) OR (“Offsite Construction”) OR (“Off-site manufacture”) OR (“Off-site manufacturing”) OR (“Offsite manufactu*”) OR (“Off site manufactu*”) OR (“Off-site manufactu*”).

Data was exported from Scopus to VOSViewer for bibliometric analysis to identify related keywords in this domain. Figures 4 and 5 were generated by the software. Figure 4 shows the country mapping for OSM related articles and Fig. 5 shows the results for the keywords that occur more than 3 times. Country mapping for OSM/OSC determines the pioneering countries as well as direct and indirect relationships in terms of the information flow in this domain. As shown in Fig. 4, the United Kingdom, Australia, China, Canada, and the United States are productive with direct and indirect relationships with each other. Table 2 shows countries with more than 3 publications related to OSM.

Figure 5 maps the OSM keywords and shows that none of the BIM-related keywords such as Building Information Model, Building Information Modelling, or VDC appears in the keyword mapping. This is supported by Table 3, which shows OSM keywords that occur more than three times. Therefore, it can be concluded that there is a lack of integration between BIM, digital fabrication, and OSM. Each cluster

Table 1 Key articles

Author	Year	Research theme					
		BIM	OSM/OSC	Pre-fabrication	Digital fabrication/Construction automation	Decision making	Literature review
He et al.	2021	√			√		
Wondimagegn Mengist	2020						√
Ala Nekouvaght Tak	2020	√	√	√		√	
Rui He	2020	√		√	√		
Shi An	2020	√	√	√	√	√	
M. F. Antwi-Afari	2020	√			√	√	
Sherif Abdelmageed	2020		√				√
Pablo Martinez	2019	√	√				
Xi Tang	2019	√	√				
Tsvetomila Duncheva	2019		√			√	
Xianfei Yin	2019	√	√				√
Xiao Li	2019	√		√			
A. Q. Gbadamosi	2019	√	√	√	√		
A. Q. Gbadamosi	2019	√				√	
Yingbo Ji	2019	√	√	√			
Jeremy Bowmaster	2019		√		√		√
Ibrahim Y. Wuni	2019		√	√		√	√
Yidnekachew T. Daget	2019			√		√	√
J. S. Goulding et al.	2019		√	√			
Lee et al.	2019	√			√		

(continued)

Table 1 (continued)

Author	Year	Research theme					
		BIM	OSM/OSC	Pre-fabrication	Digital fabrication/Construction automation	Decision making	Literature review
Daget et al.	2019		√	√		√	
Liu et al.	2019	√	√	√	√		
Alwisy et al.	2019	√	√	√			
Liu et al.	2018	√	√	√		√	
Ruoyu Jin	2018		√				√
Bon-Gang Hwanga	2018			√		√	
M. Reza Hosseinia	2018		√				√
Hamid et al.	2018	√			√		
Hwang et al.	2018		√	√		√	
Antwi-Afari et al.	2018	√				√	
Yuan et al.	2018	√	√	√			
Liu et al.	2017	√	√	√	√		
F. H. Abanda	2017	√	√				
Salama et al.	2017		√			√	
Singh et al.	2017	√	√	√			
Azadeh Fallahi	2016			√			
Liu et al.	2015	√					
Lieyun Ding	2014	√	√		√		
James T. O'Connor	2014		√	√		√	

(continued)

Table 1 (continued)

Author	Year	Research theme					
		BIM	OSM/OSC	Pre-fabrication	Digital fabrication/Construction automation	Decision making	Literature review
Caneparo et al.	2014		√	√	√		
Nawari O. Nawari,	2012	√	√	√			
Yingbo Ji	2010						√
Agkathidis et al.	2010		√	√	√		
Iwamoto	2009		√	√	√		
Jeoing et al.	2009	√	√				
Karner	2008	√	√	√			

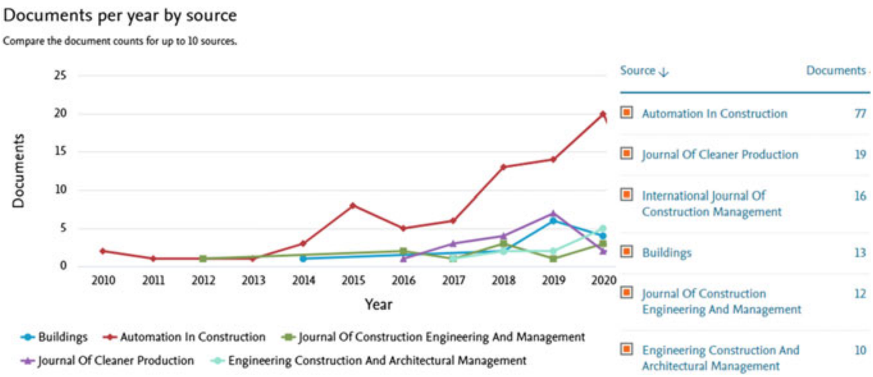

Fig. 2 OSM within BIM-related publications per year

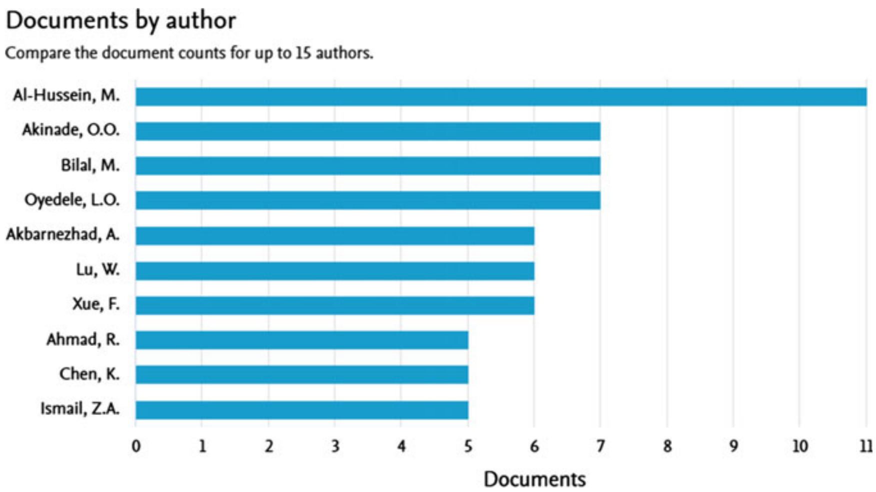

Fig. 3 Pioneer authors with a minimum of 5 publications in OSM within BIM

Fig. 4 Country mapping for OSM related articles

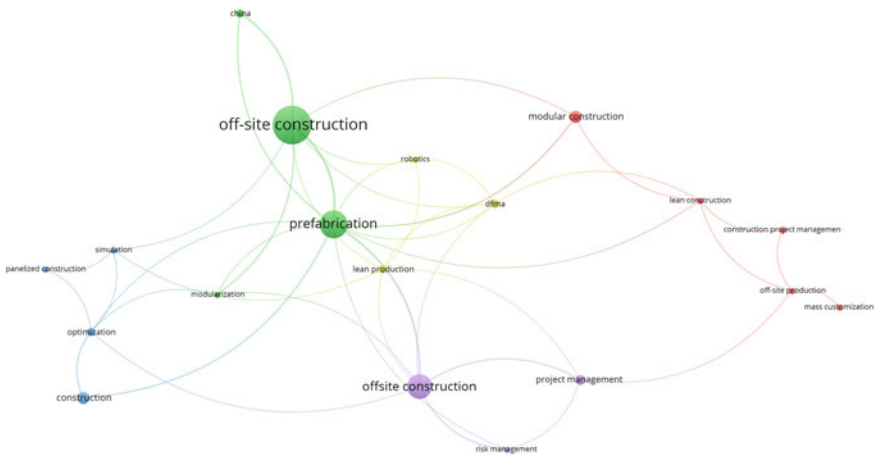

Fig. 5 OSM keywords mapping

Table 2 Countries with more than 3 publications related to OSM

Country	Numbers of article	Citations	Total link strength
Australia	29	476	131
United Kingdom	27	385	90
Canada	16	252	38
China	16	384	82
Hong Kong	11	241	69
United States	11	132	57
South Korea	6	55	9
Singapore	3	71	19

is represented by a different color. However, one specific keyword could appear in two different clusters due to a different spelling, for instance "offsite construction" or "off-site construction".

Table 3 shows occurrences resulting in more than 3 times and total link strength in the OSM cluster. Off-site construction, prefabrication, and modular construction have a high link strength and this is also in line with results shown in Fig. 5. The first four keywords in Table 3 were selected to identify the main papers for the qualitative analysis that is discussed in the following section.

Table 3 OSM keyword occurrences, more than 3 times in total

Keyword	Occurrences	Total link strength
Off-site construction, offsite construction	34	27
Prefabrication	15	21
Off-site manufacturing, off-site production	9	8
Modular construction, modularization	9	9
Project management, construction project management	8	7
Lean production, lean construction	7	11
DFMA	4	6
Optimization	4	7
Mass customization	3	1
Panelized construction	3	2
Risk management	3	4
Robotics	3	4
Simulation	3	4

4 Qualitative Analysis

The qualitative analysis discussed in this study is part of an on-going research project, which aims to identify critical success factors for the application of BIM and digital fabrication in OSM. Therefore, it is necessary to investigate and analyze the key articles in this domain to identify potential success factors. An analysis of keyword clusters in the domains of BIM and OSM helps to identify trends and the current status of the application of BIM and digital fabrication focusing on OSM. The classification of the research theme presented in Table 1 shows the direction and focus of each study based on the extracted keywords as well as initial abstract reading. A keyword co-occurrence analysis could determine the core research focus in this domain [8]. Figure 5 shows the direct and indirect relationships between keywords. Figure 2 is in accordance with Table 1, which shows that the integration of BIM and OSM has become more prominent during the past few years, mostly after the year 2016. In this section, the prominent research clusters identified by the bibliometric approach were qualitatively analyzed as discussed in the following subsection. In other words, quantitative and automatic keyword index clustering was combined with a qualitative analysis of the key publications based on all titles, abstract and full paper set.

4.1 Combination of BIM, Digital Fabrication and OSM

Selected key publications identified by the bibliometric approach were sorted by year of publication and then categorized into six research themes. All documents related to at least two of these themes were selected for more in-depth analysis. The main focus of the nominated articles was a combination of OSC and modern technologies such as BIM and digital fabrication in OSM. However, the pioneer scholars use different terminologies and approaches as we shall discuss below.

Off-site manufacturing is the process of manufacturing a construction project's component(s) at a location different from the final point of construction assembly (PCA). It involves the delivery of components to the PCA for installation at various stages of the project life cycle [11]. In the literature, different terminologies describe off-site manufacturing i.e., off-site construction (OSC), modern method of construction (MMC), off-site production (OSP), and offsite prefabrication.

As stated by Liu et al. [12], OSC integrates the application of modern technology and advanced machinery in a controlled facility at a location other than the final place of installation. The combination of manufacturing technologies and advanced machinery in prefabrication and OSM can increase efficiency [12]. Moreover, the combination of Design for Manufacturing and Assembly (DFMA) with parametric design of BIM can optimize design systems to be suitable for prefabricated buildings [13].

Putting the accent on 'manufacturing', the Construction Industry Council defines off-site manufacturing as "*a delivery method that adds substantial value to a product and process through factory manufacture and assembly intervention*" [14]. According to these authors, the main types of OSM are volumetric, hybrid, panellised, modular, and components and sub-assembly systems.

According to Agustí-Juan et al. [15], the use of digital fabrication in OSM is a robotics-based production process using a computer-aided design (CAD) method [15]. This is further elaborated by Agkathidis [16] who defines digital fabrication as a methodology of construction that is planned to be designed, manufactured, and assembled by utilizing digital tools [16]. However, in order to transition from the traditional way of planning and onsite construction, advanced machinery for manufacturing such as computer-numeric-controlled (CNC) machines, need to understand data generated from drawings and BIM. Therefore, designers need to understand the process and interoperability between BIM and automated machinery to utilize digital fabrication in OSM [17]. Moreover, industrial building system (IBS) is a commonly used term in OSM and digital fabrication, especially in Asia. According to He et al. [18], it is an innovative and advanced technology that shifts onsite traditional construction methodology to a controlled and factory-based location off-site, whereby improving productivity as well as efficiency in terms of production time (faster assembly), and thus reduced project cost [18].

In automated construction systems, a widely used term is additive manufacturing (AM). AM can potentially be applied in the production of large structures in digital fabrication [19]. It has been used in other sectors, such as automobile design, aerospace, and medical industries as well. However, as articulated by Ding et al. [5], in the construction industry, the AM process is only suitable for small and medium-scale manufacturing parts due to limitations in delivering many kinds of building materials [5].

Ding et al. [5] introduced a new procedure for large-scale projects in AM techniques called BIM-based Automated Construction (BIMAC) in automated construction systems and digital fabrication. BIMAC integrates modern CAD, computer-aided manufacturing (CAM), Numerical Control (NC) technology, new material technology, and BIM to increase efficiency in AM for large-scale projects.

Melenbrink et al. [20] argued on a gap between industry and academic research whereby academic proposals such as the BIMAC system concentrated on additive manufacturing or discrete assembly while industry efforts concentrated on automating conventional earthmoving equipment and embracing prefabrication [20].

There have been some efforts to increase automation in the construction sector but achieving full autonomy for the majority of construction tasks remains a thing of the distant future. Still, several important steps have been taken towards construction automation with the recent development of advanced machines designed for autonomous operation as well as a material-robot systems for specific assembly tasks [21].

Ham and Lee [22] studied the benefits of digital fabrication for construction management in terms of project management factors using the Project Management Body of Knowledge (PMBOK). The study shows that the use of digital fabrication brings many advantages to the project. Some factors are considered as challenges, such as cost reduction and control, but this does not mean that the use of digital fabrication is overall negative [22].

Current literature explores the benefits and capabilities of optimizing construction efficiency by utilizing BIM and digital fabrication in OSM. Some of the important attributes noted to improve productivity are “ease of handling and assembly” as well as reducing the “weight of parts” [23]. This can be supported by automation in construction and the use of robots for specific assembly tasks. On the other hand, BIM is capable of assisting the designers in understanding design requirements for digital fabrication and robot-based assembly systems. Therefore, integration of BIM, digital fabrication, and OSM is a way towards improving construction efficiency and it is expected that future study will investigate and develop a comprehensive system that integrates BIM and digital fabrication in OSM.

5 Conclusion and Future Work

This paper presents how the research on OSM and BIM has developed during the past decade. The study is crucial for understanding how to utilize BIM and digital fabrication in OSM and to provide research directions for further development in this domain. This research performs a systematic literature review, based on publications in BIM and OSM found in the Scopus database between 2010 and 2020. This review was limited to journal publications. Through the quantitative method, the bibliometric analysis approach deployed on BIM and OSM made it possible to establish the most recent subfields of study, namely, prefabrication, construction automation, and modular construction. The dataset was then refined and key publications related to the integration of BIM and OSM were selected for qualitative analysis. The classification of key articles into the following six main research themes, BIM, OSM/OSC, prefabrication, digital fabrication/construction automation, decision making, and literature review shows that there has been insufficient research on the integration of OSM, BIM, and digital fabrication. Limited studies have been found linking BIM and digital fabrication for OSM in construction even though benefits of BIM and digital fabrication in OSM were discussed by pioneer scholars and many studies during the past decade displayed the capability of BIM and digital fabrication in assisting the implementation of OSM activities such as planning, simulating, design evaluation, material processing, and manufacturing, transportation, and site assembly. Further research is needed to investigate what is required to integrate BIM, digital fabrication, and OSM. Aspects to be explored are interoperability and BIM design requirements for digital fabrication and its application to OSM, including identifying the uncertainties and differences between the latest academic research and current industry practices.

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Towards Occupant-Centric Facility Maintenance Management: Automated Classification of Occupant Feedback Using NLP

Mohamed Bin Alhaj, Hexu Liu, and Mohammed Sulaiman

1 Introduction

Building maintenance is an ongoing process throughout the life cycle of the building. During this stage, various building information such as building layout, specification, maintenance history, and failure information is required for facility management personnel to make timely repair and maintenance decisions [16]. Awareness of the facility layout and the equipment details is vital for selecting the appropriate technology for maintenance. In addition, occupants' complaints and feedback are crucial in the corrective maintenance of the building facilities because they inform facility maintenance (FM) professionals of the failures and facility conditions. However, effective collection of occupant feedback remains a challenge. For example, the existing facility maintenance management (FMM) system does not support precise location sharing, making the fault location identification difficult and the communication ineffective and inefficient [7, 13]. With indoor location for an occupant and equipment, FM personnel can reduce their efforts in locating the maintenance work [15]. As such, location identification is critical in case of, for example, simple work orders such as changing a light bulb in a complex building or locate the specification of complex equipment in front of occupants. The rise of social networks and their messaging application provide a new yet challenging tool for communication in current practice. Many governments and private sectors adopt social media on their website to encourage smooth communication [9]. In the context of FMM, the use of social networks is a relatively new approach, and many challenges are existing.

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S. Walbridge et al. (eds.), *Proceedings of the Canadian Society of Civil Engineering Annual Conference 2021*, Lecture Notes in Civil Engineering 247,
https://doi.org/10.1007/978-981-19-0968-9_24

Occupant-centric maintenance is a part of the cognitive FM system; the occupant has a role in each layer of the cognitive FM, specifically in the evaluation layer where users and FM personal can interact via social networks [27]. In this context, the widespread use of mobile devices for data collection may allow for more occupant-centric applications [18]. Additionally, mobile social networks (MSN) have the advantage over the traditional social network, leveraging the features of the smartphones, such as GPS, Wi-Fi, Bluetooth, and sensors [10]. These technologies provide a considerable amount of data that FM could not collect via traditional social networks. With mobile social networks and natural language-like occupant feedback, the natural language process (NLP) technology will assist in automated data collection and text classification. Recently, many organizations applied NLP and machine learning techniques, especially with the fast spread of social media. NLP helps retrieve useful information and reduce manual intervention using automated processes [5]. The objective of this research is to build an NLP-based model for the classification of textual work orders in Weka.

The remaining of the paper is organized as follows. Section 2 describes the previous research related to occupant-centric, social network, and NLP applications. Section 3 explains the method selection, data collection and preprocessing, and data classification. The outcome of each step of data collection and classification results is presented in Sect. 4. Finally, the conclusion section highlights the importance of the results obtained and how it benefits future research.

2 Related Work

2.1 Social Networks

The development in information communication technology (ICT) offers a promising way for people to interact effectively. One of the growing fields is social networks, which allow users to share their interests via text, photo, and video and tag their specific location. Especially, social networks have become more accessible via smartphones and natural language processing over decades [23]. Soiraya et al. [21] investigated the use of data mining to detect spam on Facebook applications. However, the precision of the testing set was 61–63% due to the small training set. Barros et al. [3] leveraged a social network application with geotagged photo and GPS tracking to study visitor behavior in a national park. This study is related to park managers and shows social networks application offers great potentials for a wide range of user-centric studies. As such, the presented research focuses on mobile social networks and how to retrieve location-specific occupants' feedback automatically using NLP.

2.2 Natural Language Processing

NLP technology is a combination of three sciences: computer science, linguistics, and mathematics that transfer human language to computer language with useful information being extracted and analyzed [26]. Text classification is one of many NLP tasks that use machine learning tools with supervised or unsupervised learning [12]. Weka is a data mining tool that uses machine learning algorithms for processing, classification, clustering, and visualization [25]. Umair et al. [24] explored the possibility of machine learning for forensic investigation on Facebook messenger. Their objective was to classify the user relationship strength on the contact list, the accuracy of the algorithms used vary between 69 and 100%. Mo et al. [14] used NLP for automated staff assignment, the reported result shows an accuracy between 77% for predicting work order and 88% for predicting priorities. Aldwairi and Alwahedi [1] utilized Weka to detect fake news in social media networks, the accuracy for the tested algorithms ranges from 94 to 99%. Bouabdallaoui et al. [5] used NLP and ML to classify maintenance requests in the FM industry based on historical data from health care facilities. The result of multiple NLP shows an average accuracy of 78%. From the papers mentioned above, it is clear that NLP is an interdisciplinary field. The accuracy result acquired ranges between 70 and 100%, which indicates that each case has a different setup affecting the result. Also, reaching 100% accuracy in previous research supports the decision of choosing NLP for automated data processing.

2.3 Occupant-Centric FM

Occupant-centric FM is a relatively new concept, and it gained attention as the technology advanced in ICT, IoT, and smart devices. Using IoT and smartphones boosts the end users' involvement in occupant-centric experimentation since smartphones can provide both sensing abilities and user interaction [17]. Naylor et al. [18] conducted a review on how the occupant-centric contribute to reducing energy use by highlighting current issues and emerging technology to enhance the performance of occupant-centric for building control. O'Brien et al. [19] provided a performance metric to assess building energy based on occupant-centric perspective using actual and simulated data samples. The focus of the mentioned article was on monitoring and reducing energy use. Park et al. [20] conducted a critical review on occupant-centric control, specifically the field implementation. The study highlights the limitation of field study related to the reluctance of FM to adopt new technology that requires installing new sensors and systems, which might affect the existing system and cause malfunction. It is clear that the occupant-centric in FM has not reached a mature level and requires more effort to explore and validate new approaches.

3 Methodology

Social networks application nowadays has become a big data source that can be analyzed to gain new knowledge. This research investigates the use of mobile social network applications for data collection and location sharing in FMM. Specifically, this research develops a natural language processing (NLP)-based machine learning algorithm to automatically classify occupant feedback from the social network application. The accessibility of social network applications is relatively more straightforward than the current reporting system for FMM. It should be noted that a survey was conducted in authors' previous research to identify the most popular platform with other factors [4]. Facebook was the most popular social media platform on campus. Consequently, we chose to select Facebook messenger for the case study. The popularity of Facebook was not the only reason for our choice, but it has many advantages over the other social network platforms. For example, the Facebook developer supports many features to build an application that retrieves real-time data from the messenger platform using the Application programming interface (API) tool. Figure 1 illustrates the methodology. The first phase is data collection using social media applications; then, data retrieval and classification in the second phase, where an API tool and Weka are employed. The third phase is data processing at the FM center based on the automated classification. Each step in the proposed methodology is described in detail in the following subsections.

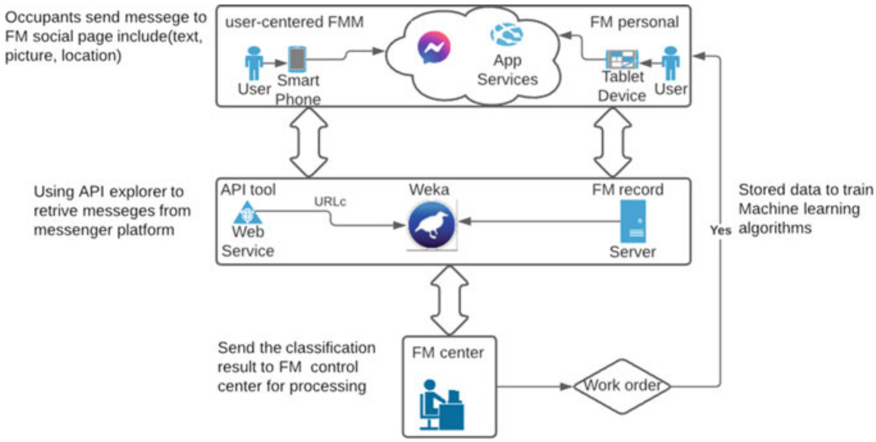

Fig. 1 Occupant-centric and NLP framework for FMM

3.1 *Data Collection and Preprocessing*

The first step is data collection, where end-users send a text message via messenger. The text message includes three main categories, namely: (1) the room number, (2) the problem description, and (3) share their location. In addition, end-users can attach a picture of the reporting problem. This method encourages the occupant of the facility to be more active in reporting a facility-related issue. Figure 2 illustrates this step.

The second step uses the API tool in the developer page to stream the data from the facility messenger platform. The API tool is designed to retrieve or send data to the connected page. To retrieve the data from the messenger, a Facebook business page is required to stream real-time data from the page or messenger platform. Then, a developer account needs to be created and connected with the business page. After that, a new application and webhook are created to get an access token for a secure connection to manage and retrieve data using the API tool. More detailed steps and descriptions can be accessed in this link https://developers.facebook.com/docs/messenger-platform/getting-started/app-setup. The data can be streamed to the API page and the cURL, and the code can be accessed in many formats, as shown in Fig. 3.

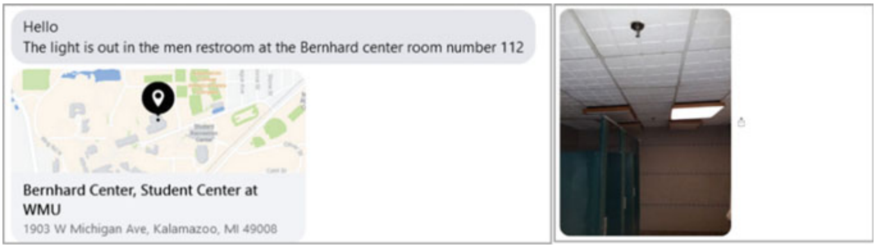

Fig. 2 A screenshot of end-user reporting issues via messenger

Fig. 3 The inquiry of API in code format

Table 1 Sample of deleted data

Trade	Reported issue/comments/scheduled maintenance
Electrician	Repair lights in the corridor
Environ. control	EF-5 status does not match the command
Environ. control	PM (60 days)—inspect freeze stats for operability
Millwright/Maint. mech	PM (5 days)—weekly all mechanical equipment in CoEAS and paper pilot
Millwright/Maint. mech	RO water is in alarm
Plumber	Water leak
Refrigeration repair	Replace boiler
Millwright/Maint. mech	Please repair the pressure regulator. Thank you
Pipefitter	Receivers are leaking in this area. Please inspect and fix. Thanks
Skilled trades helper	Please check the penthouse for leaks from coils

Machine learning algorithms need to be trained and tested to evaluate the performance of the choosing algorithm. At this stage, the data collected manually from the facility management website and stored in an excel file for preprocessing and cleaning. The cleaning process includes deleting duplicate orders, FM comments, scheduled maintenance, and unassigned work orders. Table 1 contains a sample of the unnecessary data that has been filtered. Also, we edited the signs that consider part of the programing for Weka, such as (‘,”), and replace them with the appropriate meaning, whether it is inch, feet, or quotation sign. Table 2 shows samples of the data after the filtering and cleaning process.

3.2 Data Classification

Classification is a known approach for supervised learning to set of data has labels, or part of the data has labels. The classification process began with training the algorithms with a set of data that has the class for each element. Then the algorithm builds a model to automatically classify a new group of data [2]. Each request submitted to the FM website needs to be assigned to a trade. Trade herein is the maintenance team responsible for specific trades such as electrician, plumber, carpenter, and the like. To train machine learning for request classification, Waikato Environment for Knowledge Analysis (Weka) is utilized. Weka is a data mining tool that uses machine learning for classification [8]. The data was divided into 355 training sets and 65 testing sets. The most applied and suitable algorithms for classifying social networks data, such as logistic [4], support vector machine, Naïve base, and the random forest, has been tested [11].

Table 2 Sample of the data after filtering

Trade	Action requested
Electrician	There are two lights out in this office B-265. This office is inside of room B-237. One is a ballast issue. Please insp. and fix ASAP since I believe these are the only two lights in the office. Thanks
Appliance repair	Floyd hall, F-205 mens bathroom paper towel holder, when you pull the paper towel it gets stuck and wont come down it goes back up inside. Per Custodian Calvin Jones
Plumber	Floyd hall, 1st floor—west drinking fountain across from student study area C-126 is plugged, water is going down very slowly. Per Custodian P. Thomas category: plumbing and bath item: other/miscellaneous problem: other
Electrician	We just had someone in and replace the ballast on a set of lights and now it is out again. Category: electrical and lighting item: interior lighting problem: light bulb is out
Plumber	Water is leaking/dripping into the main entrance area from the entrance roof. I believe that the roof drain is clogged with leaves which allows the water to go over the seal and leak into the lobby. It is currently about a 5 ft by 5 ft puddle to the left as you enter the building, still dripping in with rain expected all week. Please clean up water and inspect roof drain. Thank you category: other item: other/miscellaneous problem: other
Carpenter	Parkview Cafe exterior door–the weather stripping ripped off the door completely. Please install new stripping. Category: doors and locks item: exterior door problem: other problem
Carpenter	Sent to shop 6 Parkview Cafe exterior door–the weather stripping ripped off the door completely. Please install new stripping. Category: doors and locks item: exterior door problem: other problem
Plumber	DI Faucet broken will not close category: plumbing and bath item: faucet problem: other problem
Electrician	Lights out on the exterior of pilot plant—one above the Parkview room and 7–8 along the parking lot berm_notes: *Attachment* category: electrical and lighting item: exterior lighting problem: light bulb is out

4 Result

In this section, we discuss the result of the API tool and the classification using Weka. The API tools allow us to inquire about specific information sent or posted on the Facebook page or sent using messenger. In order to acquire the messages from the Facebook messenger platform, permission needs to be granted from Facebook to access users' messages. This step is called an App review and takes up to five days to be approved or denied the right to access messages. However, general information such as users name, photo, about, location, and the information the users make visible to the public can be retrieved without special permission, as shown in Fig. 4. Access token and permission is to enhance security and to protect user's privacy, which is a critical issue for users and organizations. The API tools provide access to the code in different formats from (Get Code) so the developer can carry out more data analysis.

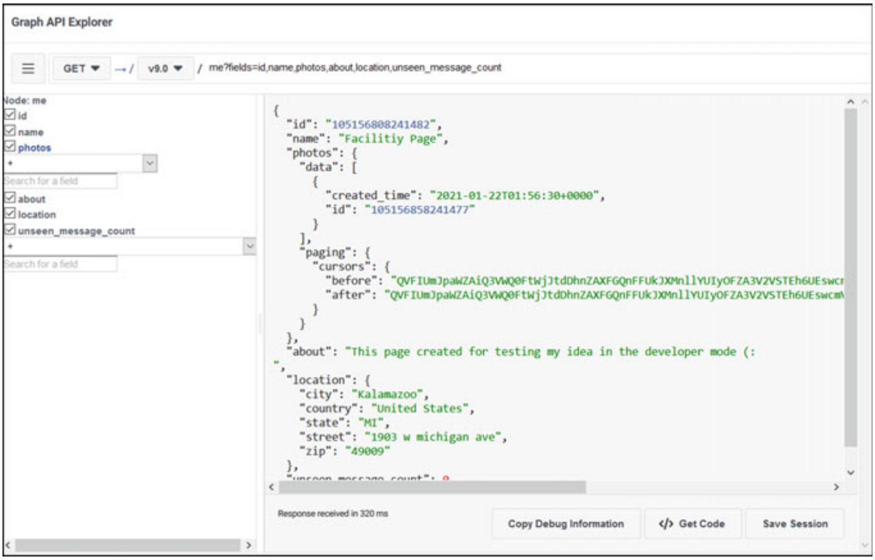

Fig. 4 API tool simple inquiry

To extract useful information, Weka has been used to train and test historical data from the FMM website. A supervised machine learning technique is utilized to evaluate the performance of the chosen algorithms. Weka provides statistical measures such as accuracy, Kappa, and F-measure to evaluate the model performance. Kappa is a performance metric measuring the accuracy of the predicted classes where 1 indicates a completely accurate result. Table 3 shows that random forest, Logistic, and SVM algorithms achieved a 100% accuracy for the tested data set. In contrast, naïve base and J48 score (87.69% and 49.23%) accuracy and kappa (0 and 0.80) of the tested data set. Figure 5 shows the confusion matrix for training and testing data sets for Random forest algorithms. Each column shows the predicted label (Trade) in the confusion matrix, and the raw shows the actual label. The diagonal line indicates the correctly classified instances where the expected label matched the actual label [6].

Table 3 Accuracy, Kappa, and F-measure for the tested algorithms

Algorithm	Accuracy (%)	Kapa	F-measure
Random forest	100	1	1
J48	49.23	0	0.66
Naïve base	87.69	0.80	0.88
Logistic	100	1	1
SVM	100	1	1

```
=== Confusion Matrix ===

   a   b   c   d   e   f   <-- classified as
 146   1   0   0   0   0 |   a = ELECTRICIAN
   0  40   0   0   0   0 |   b = APPLIANCE REPAIR
   0   0  70   0   0   0 |   c = PLUMBER
   0   0   0  69   0   0 |   d = CARPENTER
   0   0   1   0  18   0 |   e = CUSTODIAN
   0   0   0   0   0  10 |   f = LOCKSMITH
```

```
=== Confusion Matrix ===

  a  b  c  d  e  f   <-- classified as
 32  0  0  0  0  0 |  a = ELECTRICIAN
  0  3  0  0  0  0 |  b = APPLIANCE REPAIR
  0  0 14  0  0  0 |  c = PLUMBER
  0  0  0 11  0  0 |  d = CARPENTER
  0  0  0  0  4  0 |  e = CUSTODIAN
  0  0  0  0  0  1 |  f = LOCKSMITH
```

Fig. 5 Confusion matrix for random forest training (left), testing (right)

5 Conclusion

The current FM practice relies on the occupant complain and feedback in the corrective maintenance. This makes the location for the occupant important to locate and identify the failure location. This paper explores the use of mobile social networks for FMM to retrieve real-time information using a messenger platform and machine learning. The result shows 100% accuracy for three of the algorithms that have been tested, namely, random forest, Logistic, and SVM. The performance of these algorithms encourages conducting more research and experiments on NLP. Weka also provides statistical measures to evaluate the model performance, such as Kapa and F-measure, to validate the classification results further. As illustrated above, the data can be streamed using the API tools to retrieve real-time information from the messenger. However, due to the limitation applied on the Facebook developer for individual verification, the case study could not be carried out for the full sequences even though the technical process is feasible in normal circumstances. Future work will focus on developing a stand-alone social network application dedicated to FMM supporting location-specific occupant feedback.

Acknowledgements The authors are grateful for the ongoing support from the facility management center by making the data available to the research team.

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Auto-positioning of UWB RTLS for Construction Site Applications

T. Jin, F. Sadeghpour, and G. Jergeas

1 Introduction

TOF-based UWB has been concluded with higher practicality on construction site application compared with the most commonly investigated TDOA/AOA-based UWB RTLS [1]. Unlike TDOA/AOA-based UWB, the TOF-based UWB does not require any time cables for time synchronization, which could avoid triggering extra clutter and tripping hazard and restricting the installation location of anchors [2–4]. Moreover, no reference tag is required in TOF-based UWB. For many TDOA/AOA-based UWB utilizing reference tag, a clear Line-Of-Site (LOS) between the reference tag and the anchors has to be maintained during the entire location estimation process for accurate calibration [5–9]. From the perspective of economical widespread application, the cost of the TOF-based UWB RTLS is decreased by approximately 95% of the TDOA-based systems [7, 10, 11].

Except for the above advantages on practical construction site applications, the auto-positioning, in particular, as a unique feature of TOF-based UWB RTLS, enables the system to automatically compute the relative locations of anchors and eliminate the necessity of precise measurements at the setup stage. For UWB RTLS, the anchor locations need to be predetermined to set up the relative coordinate for the tracking system. Survey tools such as Total Station are typically utilized to determine the locations of the anchors. Due to the dynamic nature of construction sites, it is inevitable to frequently move the anchors during the dynamic construction phases [12]. Nevertheless, it is not practical to keep repeating the similar survey process throughout the construction process. The auto-positioning of the UWB RTLS can automatically determine the relative locations of all anchors. This greatly simplifies the process of applying UWB RTLS in frequently updated construction sites. The

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S. Walbridge et al. (eds.), *Proceedings of the Canadian Society of Civil Engineering Annual Conference 2021*, Lecture Notes in Civil Engineering 247,
https://doi.org/10.1007/978-981-19-0968-9_25

TOF-based UWB RTLS enables the auto-positioning on account of the two-way ranging performed between anchors. Other location estimation methods, including AOA (Angle of Arrival) and TDOA (Time Difference of Arrival), have no capability to perform auto-positioning.

The objective of this study is to assess the location estimation accuracy of tags under auto-positioning mode and compare it with the scenario when auto-positioning is not utilized. By demonstrating the mechanism of auto-positioning, the source of the induced inaccuracy is illustrated. In addition to that, the potentials of enhancing accuracy under auto-positioning are also presented.

2 Literature Review: Requirements and the Importance of Accuracy on UWB RTLS for Construction Site Applications

2.1 Requirements on UWB RTLS for Construction Site Applications

UWB RTLS were confirmed with great potentials for construction site applications by studies in the past decade [3, 5, 6, 13–16]. Studies also concluded the practicality requirements on UWB RTLS for construction site applications: accuracy, power source, robustness (NLOS), scalability (size and weight of the device), frequency band, storage, and cost [2, 3, 10, 17].

However, another aspect of the practicality of the UWB RTLS has to be considered for construction site application: the simplicity of its utilization. The construction sites have dynamic characteristics both spatially and timely in nature [15, 18–21]. Andayesh and Sadeghpour [18] conducted a comparative analysis regarding the static, dynamic, and phased models for site layout [18]. Except for the reflection on the changes on different locations spatially, the changes versus the time dimension are stressed across different construction phases. An accuracy assessment of a TDOA-based UWB RTLS was conducted by Shahi et al. [22] to illustrate the influence across an increasingly more congested piping project [22]. As the environment becomes more congested, the anchors have to be reconfigured almost along a line in their study. The frequent changes on the construction environment will frequently change the deployment locations of the anchors due to spatial restrictions.

In addition to the spatial restrictions from the changes of the construction environment, the Line Of Sight (LOS) between the anchors and tags is another consideration. None Line Of Sight (NLOS) has been confirmed as one of the predominant factors that deteriorates the location estimation accuracy of UWB RTLS [15, 22–25]. Shahi et al. [22] also demonstrated that the environment will have no influence on the location estimation accuracy as long as the direct LOS between anchors and tags are maintained [22]. Hence to achieve the high-accuracy location estimations, the anchors will need to be frequently moved across different construction phases to avoid too much unnecessary NLOS.

As aforementioned in the introduction section, the UWB RTLS requires the location of anchors to be predetermined to set up the relative coordinate. The repetitive utilization of survey tools such as Total Station will be inconvenient and unrealistic for practical application. Hence this study will investigate and propose a novel auto-positioning methodology which could automatically compute the locations of the anchors.

2.2 The Importance of Accuracy on UWB RTLS for Construction Site Applications

Accuracy, as the most important RTLS performance evaluation factor, has significant influence on its applications. For resources tracking and productivity monitoring, a number of studies demonstrated the significance of accuracy of the TDOA UWB RTLS and assessed the accuracy performance in different construction environments [5, 15, 22, 23]. For labor and equipment safety, proactive alarm systems are developed and assessed in a number of studies [6, 13]. However, false alarms due to inaccuracy of the system and delay of the signal transmission show challenges for the application of UWB RTLS [6]. These alarm systems rely on virtual fencing (VF) boundaries to define the dangerous scenarios [6]. Low accuracy UWB RTLS will increase the diameter of VF boundaries and trigger frequent false alarms. For robotics and navigation in construction sites, a number of studies utilized UWB RTLS as sensors due to its high stability and reliability in indoor environment. In these studies, the navigation errors were highly dependent on the accuracies of the UWB RTLS.

Due to the importance of accuracy, this study will assess the accuracy when the locations of anchors are determined by accurate surveying and auto-positioning respectively. By comparing the difference of accuracy performance, the inaccuracy trigger by auto-positioning will be demonstrated.

3 Methodology

3.1 Auto-positioning of Anchors

3.1.1 The Mechanism of Auto-positioning

The mechanism of TOF ranging measurement has been demonstrated in the authors' previous CSCE paper [1]. The auto-positioning conducts the same ranging measurement between anchors instead of tags. However, the auto-positioning network is much more complicated compared with the scenario when tracking a tag. For the scenario where four anchors are used to measure the tag, all the four anchor locations are known and just a tag will be needed to be computed. Different from that, when auto-positioning is conducted, all the computed anchor locations are strongly correlated. The deviated estimations on one anchor will accumulatively impact all other computed anchor locations.

The auto-positioning first set up one of the anchors as an initiator (origin (0, 0, 0)) and start the ranging measurement between the first three anchors, namely Anchor 1 (initiator), Anchor 2, and Anchor 3. In this process, all three anchors are required to be configured at the same hieght, which means for all anchors, the value on Z axis is 0. Moreover, Anchor 2 is defined to be on the same Y axis with the initiator, which means the value on the Y axis is 0. Under this circumstance, the number of unknowns are reduced to three (3), which are the x value of Anchor 2, and the (x, y) value of Anchor 3. Three anchors can comprise three ranging measurements, which is equivalent to three equations for an equation systems. Hence the system is a determined system to solve the unknown locations for the anchors (Fig. 1).

With the locations of the first three anchors determined, the other anchor (Anchor 4) is treated as a tag for trilateration (demonstrated in Fig. 2). This means that the first three anchors are utilized to measure the location of the fourth anchor. Under this scenario, the fourth anchor does not have to be on the same height (Z axis) with the first three (3) anchor because there are three ranges to compute the three unknowns (x, y, z) of the fourth anchor.

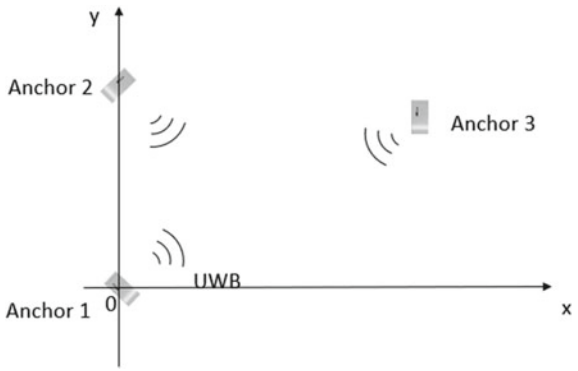

Fig. 1 Mechanism of auto-positioning

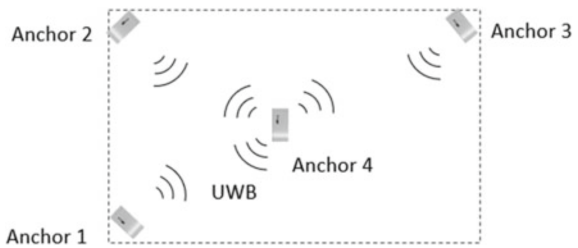

Fig. 2 Mechanism of auto-positioning

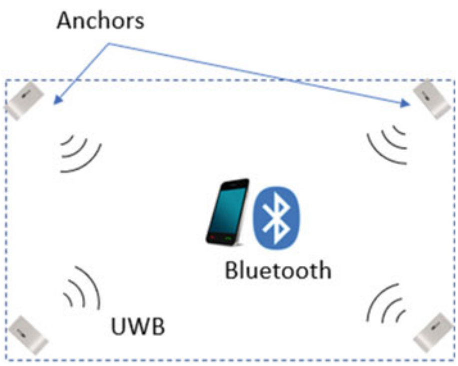

Fig. 3 Schematic diagram of auto-positioning

3.1.2 The Configuration of Auto-positioning

The two-way communication can not only be performed between a tag and an anchor, but two anchors. By computing the ranges, the anchors could automatically determine the location of each other through a virtual network. This provides a unique advantage in simplifying the installation and reinstallation of RTLS. While for systems utilizing other location estimation methods, typically survey tools such as total station is required to identify the exact anchor locations.

Auto-positioning utilizes an inherit android-based application provided by the manufacturer of the TOF-based UWB RTLS. The schematic diagram of the auto-positioning feature is demonstrated in Fig. 3. As illustrated in the figure, the mobile device communicates with the anchors by Bluetooth and the anchors measure their mutual ranges (distances) through UWB signal. To successfully apply auto-positioning, a number of procedures will be required:

1. Turn on the Bluetooth of the mobile device with the android-based system.
2. Choose the initiator among one of the anchors and select the initiator in the android application.
3. Based on the geometrical configuration of the anchors, sequence the IDs of the anchors in a clockwise order in the android application.
4. Start the auto-positioning of the anchors and save the computed locations for furtherly tracking the tags.

3.2 Accuracy Measurement

Precision and offset are two (2) commonly used measures to define accuracy. Precision represents the fluctuations of the sample with regard to the sample mean value. Offset illustrates the distance between the sample mean value to the actual data point. Neither of them provides a complete perspective on accuracy. A small precision sample can have a large offset and vice versa.

This study utilized two other measures that are also commonly used for accuracy assessment: Distance Root Mean Squared (DRMS) and Mean Radial Spherical Error (MRSE). DRMS (Eq. 1) and MRSE (Eq. 2) combine precision and offset and provide a single value to represent accuracy for two-dimensional and three-dimensional accuracy measurements:

$$DRMS = \sqrt{\sum_{i=1}^{n} (x_i - x_{Actual})^2/n + \sum_{i=1}^{n} (y_i - y_{Actual})^2/n} \tag{1}$$

$$MRSE = \sqrt{\sum_{i=1}^{n} (x_i - x_{Actual})^2/n + \sum_{i=1}^{n} (y_i - y_{Actual})^2/n + \sum_{i=1}^{n} (z_i - z_{Actual})^2/n} \tag{2}$$

where x_i, y_i, z_i represent the ith estimated location of the tag, x_{Actual}, y_{Actual}, z_{Actual} represent the actual location of the tag, and n is the number of location estimations for each tag.

4 Experiment and Analysis

The experiments are conducted in the controlled lab environment to avoid unnecessary Non-Line-Of-Sight (NLOS) impact on the location estimation accuracy. Figure 4 demonstrates the environment of the experiments carried out in this study. Four (4) anchors are configured at the corners of the Room 334. In this study, the room is surveyed with a high precision total station (±1 mm level) to show the actual locations for tags and anchors. Since there is an unmovable metal desk at one of the corners, there are 29 tag locations and four (4) anchor locations surveyed in this room (as shown in Fig. 4).

4.1 Benchmark

The object of this experiment is to provide a benchmark of the accuracy when the auto-positioning is not utilized. Since the tag location estimation process itself has inaccuracies, it needs to be computed and excluded. By comparing the benchmark experiment and auto-positioning results, the droppage of accuracy due to auto-positioning could be illustrated.

Figure 5 describes the DRMS, MRSE accuracy distributions. As it can be inferred from the figure, this UWB RTLS demonstrates high accuracy for the location estimation of the tags when applying surveying for the location of anchors. Table 1 summarizes the statistical results of the benchmark experiment. As it can be inferred

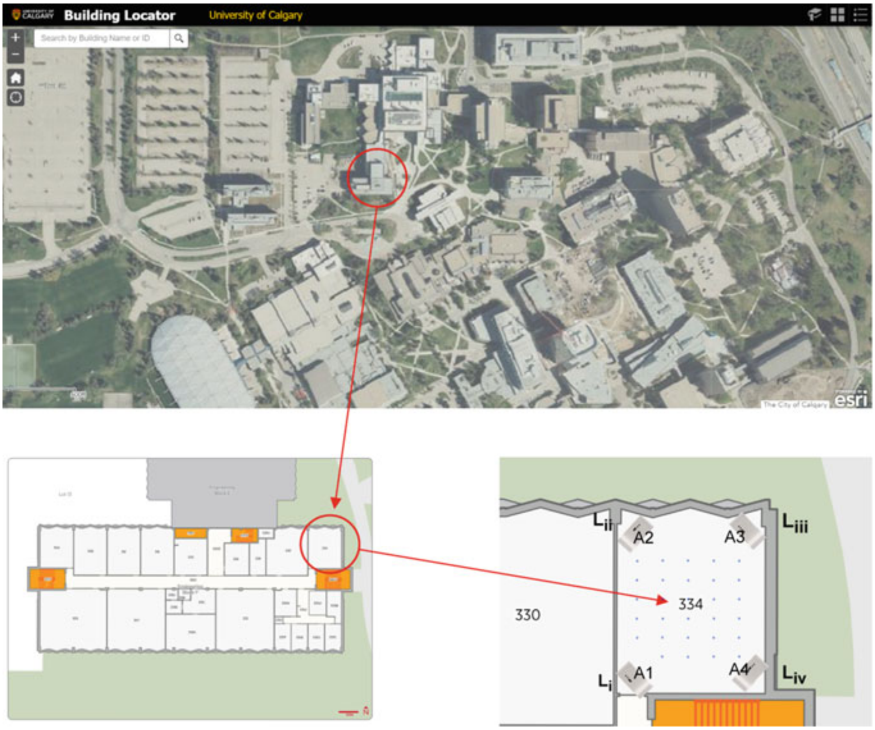

Fig. 4 Experiment environment

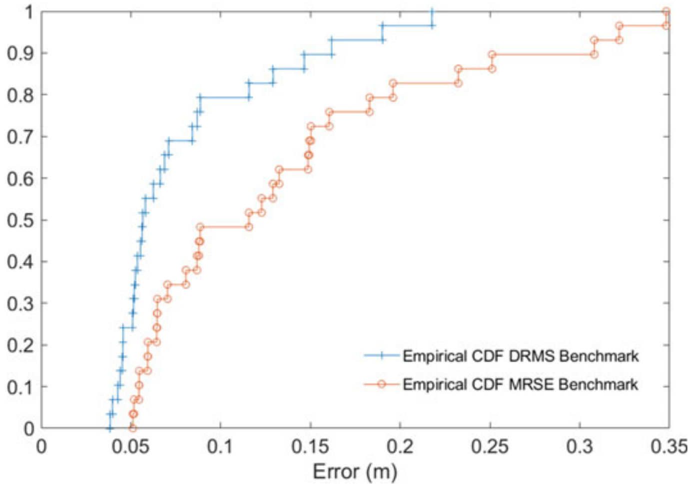

Fig. 5 Error distribution **a** DRMS, **b** MRSE

Table 1 Summary of DRMS, MRSE accuracy

	μ (m)	σ (m)	Min (m)	Max (m)
DRMS	0.079	0.047	0.038	0.218
MRSE	0.134	0.086	0.051	0.348

from the table, the average DRMS and MRSE are 7.9 cm (±4.7 cm (σ), 2D) and 13.4 cm (±8.6 cm (σ), 3D), respectively.

4.2 Auto-positioning Accuracy Assessment

Four (4) anchors A1, A2, A3 and A4 are set up at the same anchor locations as the benchmark experiment. As previously mentioned in Sect. 3.1, one of the anchors serves as an initiator (origin of the auto-positioning coordinate) whose coordinate location is considered as (0, 0, 0). To be in accordance with the benchmark experiment, A1 at anchor location Li is selected as the initiator.

Figure 6 describe the DRMS and MRSE error distribution. As can be inferred from the figure, DRMS varies from 7 to 85 cm while MRSE varies from 15 to 96 cm. Table 2 presents a comparison between the Benchmark Experiment and Test 1. As can be inferred from the table, the average DRMS and MRSE are increased by 29.1 cm and 36.7 cm respectively when auto-positioning is used.

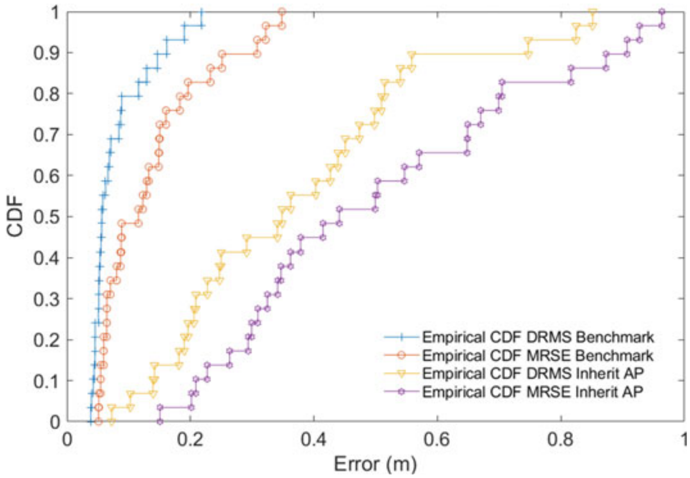

Fig. 6 Auto-positioning experiment

Table 2 Comparison between Benchmark (TS) and auto-positioning

	μ (m)	σ (m)	Min (m)	Max (m)
DRMS (TS)	0.079	0.047	0.038	0.218
MRSE (TS)	0.134	0.086	0.051	0.348
DRMS (Auto-P)	0.370	0.207	0.073	0.852
MRSE (Auto-P)	0.501	0.237	0.151	0.964
Difference of DRMS	0.291	0.160	0.035	0.634
Difference of MRSE	0.367	0.151	0.100	0.616

Table 3 Positioning errors for the location of anchors with auto-positioning

Anchor	X (m)	Y (m)
A1	0.000	0.000
A2	0.258	0.000
A3	−0.153	0.036
A4	0.256	−1.089

In the worst scenario, the location estimation accuracy is within 1 m for both two-dimensional and three-dimensional conditions. This indicates directly utilizing auto-positioning could simplify the application procedure for scenarios where meter-level accuracy is sufficient.

The source of the inaccuracy location estimation of tags under auto-positioning mode originates from the inaccuracy of anchor locations. Hence, the auto-positioning accuracy for the anchors is presented in Table 3. As it can be inferred from the table, the error can be up to approximately 1 m. Therefore, it can be concluded that the meter-level inaccuracy on the location estimation of the tags originates from the meter-level inaccuracy of anchor locations. Therefore, to increase the location estimation accuracy for the tags, the major task for future studies is to enhance the auto-positioning accuracy for the anchors.

5 Conclusion

As a unique feature for TOF-based UWB RTLS, the functionality of auto-positioning was confirmed in this study. Through the auto-positioning of anchors, the application of UWB RTLS has the potential to be significantly simplified by eliminating the need of repeating surveying the locations of anchors. The application of auto-positioning induced an increasement of inaccuracies (7–85 cm DRMS (2D) and 15–95 cm MRSE (3D)). In the worst-case scenario, the location estimation accuracy is within 1 m for both 2D and 3D conditions. This suggests that directly utilizing auto-positioning could simplify the application procedure for scenarios where meter-level accuracy is sufficient. This study proposed the potentials of auto-positioning on simplifying the configuration of the UWB RTLS on construction project. Even if the auto-positioning induces errors for location estimations, it provides a direction on how to simplify the application of UWB. In addition, this study also enables a reference for future studies to improve the location estimation accuracy under dynamic mode.

Acknowledgements The authors would like to acknowledge the National Science and Engineering Research Council (NSERC) for the support of this research.

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Automated Ergonomics-Based Productivity Analysis for Intelligent Manufacturing in Industrialized Construction

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1 Introduction

During the last decade, industrialized construction, which includes methods such as modular construction and panelized construction, has become increasingly popular around the world. These recent innovations to the traditional construction approach have provided benefits in terms of improved productivity, a controlled working environment, reduced waste, and a reduced physical workload in a more ergonomically friendly context [10]. In current practice, many industrial construction enterprises are implementing intelligent manufacturing in the form of automated construction machinery and other advanced technologies, such as the use of a vision-based system to complete automatic inspections for safety and product quality [7]. The cycle times of production in a machine environment can be easily extracted and controlled. However, the cycle times of manual operations are usually collected through observation using a time study, which is time-consuming, inconsistent, and error-prone, given the complex working environment [2].

Considering the aforementioned limitations and the goal of achieving a stable working environment, the automation of both the ergonomic risk assessment and productivity analysis of manual operations is in high demand in the context of

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S. Walbridge et al. (eds.), *Proceedings of the Canadian Society of Civil Engineering Annual Conference 2021*, Lecture Notes in Civil Engineering 247,
https://doi.org/10.1007/978-981-19-0968-9_26

intelligent manufacturing in industrialized construction. Even in an industrialized construction context, workers perform repetitive tasks, and there are many physically demanding tasks that cannot be fully replaced by machines and robotic arms. Workers are thus exposed to the risk of developing work-related musculoskeletal disorders (WMSDs). These repetitive manual activities require accurate ergonomic risk assessment and motion time analysis to ensure ergonomic safety and reliable planning and scheduling. With the support of 3D modelling technology, automating the ergonomic risk assessments of manual operations in the context of industrialized construction has proven to be a successful strategy [5, 6, 18] when combined with rapid entire body assessment (REBA) [4] and rapid upper limb assessment (RULA) [9]. The accuracy of the 3D modelling-based method has been improved by integrating it with fuzzy logic to address human perception issues in the postural data collection process [17, 18]. However, some user inputs, such as degree of repetitiveness, are still required in the current method, and this may affect the assessment results. Moreover, the reliability of the estimation of cycle times of manual operations is subject to various productivity-influencing factors (i.e., external, management, human, and technical factors) that change with the increasing complexity of the work environment and the difficulties involved in acquiring measurements [3]. Thus, an accurate and automated method of estimating cycle times is essential for computing the degree of repetitiveness of the manual operations in order to achieve full automation of ergonomic risk assessments and to improve the accuracy of the assessment results. Accurate estimation of the cycle times of operations in industrialized construction can also be used to evaluate productivity.

2 Literature Review

The purpose of this section is to provide an overall understanding of the previous research in this area as well as to provide a rationale for the choice of the cycle time estimation method used in the present research. We begin with a definition of productivity, followed by a review of previous productivity analysis methods, and finally a review of automatic motion analysis methods for productivity analysis.

2.1 Definition of Productivity

Productivity can be defined in many ways. In construction manufacturing, productivity usually refers to labour productivity, which is calculated by quantifying the units of work produced per man-hour [12]. The measurement of labour productivity, though, differs depending on the economic model, project-specific model, or activity-oriented model applied [14]. In a construction manufacturing facility, activity-oriented models are typically employed to measure labour productivity.

Labour productivity is determined by the workhours incurred, which in turn is a function of the cycle time of manual operations required to finish the unit of work.

2.2 Previous Productivity Analysis Methods

Various techniques, including activity sampling, foreman delay surveys, time study, motion analysis, and group timing [12], are used to measure productivity. The accuracy of the productivity measurement, though, is governed by the reliability of the time data collected. Furthermore, these traditional techniques rely on personal judgment, which involves the estimator's perception of the time required for the manual task. Although these methods lead to highly subjective and unreliable results, the time study technique in particular is still commonly used in construction manufacturing facilities due to its simplicity and effectiveness. However, it is time-consuming and error-prone when employed in a complex working environment.

The motion analysis technique is also commonly used for collecting motion times during manual operations. Predetermined motion time systems (PMTSs) provide standard cycle times for physical operations by characterizing the working method and procedure. PMTSs are widely used in various industries for setting production standards (together with time studies, work sampling, and standard data). PMTSs are based on an engineered work measurement, which is essential for cost estimation, work planning and scheduling, and decision making [2]. They are capable of providing process times in the planning phase, and of facilitating the design of work systems in a targeted manner.

The commonly used PMTSs in current practice include methods-time measurement (MTM) [8], the Maynard operation sequence technique (MOST) [19], and the modular arrangement of predetermined time standards (MODAPTS) technique [13]. These methods can be distinguished with respect to the level of precision, the scope of data application, the classification of motion, and the unit of time used [2]. The majority of PMTSs, though, do not sufficiently address the impacts of time standards, including various task variables, worker variables, and environmental variables [2]. In addition to these deficiencies, PMTSs are time-consuming and difficult to apply, necessitating specialized training [2].

2.3 Automatic Motion Time Analysis Method for Productivity Analysis

PMTSs have been employed in various manufacturing contexts to predict assembly task cycle times. The use of PMTSs has brought considerable benefits in the field of automobile manufacturing [11, 15]. Despite the wide and successful application of PMTSs in other industries, though, these methods have seldom been utilized in the construction manufacturing industry due to the dynamic nature of the construction production facility.

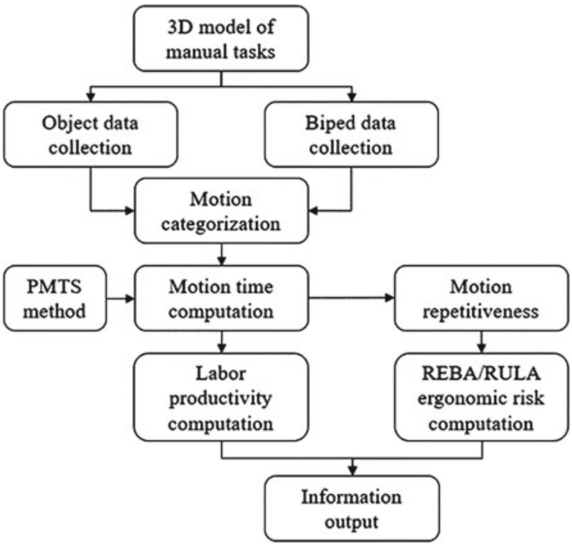
The time and motion analysis originated in industrial engineering, where production occurs in a steady-state environment [14]. An industrialized construction setting in which intelligent manufacturing methods are employed offers a stable working environment and, hence, the opportunity to apply PMTSs when conducting productivity analyses. In construction manufacturing, MODAPTS has been successfully integrated with discrete-event simulation modelling yielding reliable estimates of manual task durations [3]. However, this integrated method is not fully automated and requires specialized knowledge of simulation modelling.

The present research proposes an automatic productivity measurement method that leverages 3D modelling. The method provides accurate and objective productivity measurement of manual operations in construction, in contrast to traditional on-site methods, which are unreliable and contingent upon personal judgment. The proposed method can also be used to evaluate the degree of motion repetitiveness in tasks in order to improve the accuracy and level of automation of ergonomic risk assessments using 3D modelling.

3 Methodology

The aim of the proposed PMTS-based motion time analysis system, summarized in Fig. 1, is to measure productivity accurately and automatically using 3D modelling. The method begins with the 3D modelling of manual operations. Both object data and biped data are collected and formatted based on a 3D biped model. The motions

Fig. 1 Overview of automated ergonomics-based productivity analysis method



are then categorized based on all the biped and object coordinates' movements in the animation. The required motion time is computed according to the criteria in the selected PMTS method (in this case, MTM-1). Then, labour productivity is calculated according to the definition commonly used in construction (i.e., output as a ratio of work hours inputted). Also, the degree of repetitiveness of the motions involved in the tasks under study is assessed for the purpose of identifying candidate motions for automated ergonomic risk assessment (i.e., REBA and RULA). Finally, information pertaining to labour productivity and the corresponding ergonomic risk of the animated task is outputted for further analysis.

3.1 Automatic Motion Time Analysis

The automatic motion time analysis proposed here is based on PMTS methods. As mentioned above, the PMTS method selected in the present research is the MTM-1 method, which is a quantitative analysis method encompassing all the basic human body motions. The MTM-1 system has its own base measuring unit, called the time measurement unit (TMU), which is equal to 0.036 s. The input requirements of the MTM-1 system are motion types, influencing factors, and motion cases. Table 1 summarizes the pertinent information for hand motion in the MTM-1 system [1, 8]. It should be noted that the required inputs are still determined based on the user's experience and knowledge of the given movement. In consideration of this, to avoid subjective inputs we develop a motion categorization process based on the rules for basic motions in the MTM-1 system.

In the 3D model, the biped data and object data are extracted and saved separately in the MAXScript programming environment. Python programming language, with its extensive support libraries, is used to effectively process, organize, and compute the data. Rule-based motion categorization is applied using the logical operators, AND, OR, and NOT, to automatically identify the given motion at each time frame. In the present research, it should be noted, "*Carry*" is a status that refers to the biped

Table 1 Summary of five basic hand motions as represented in MTM-1 system

Motion	Symbol	Description	Factor	Time TMU
Reach	R	Movement of the hand or fingers	Motion length, motion case	1.6–26.7
Move	M	Relocating an object	Motion length, motion case, object weight	1.7–62.05
Grasp	G	Grasping an object	Motion case	0–12.9
Position	P	Align, orient, or engage an object to another	Class of fit, symmetry case, ease of handling	5.6–53.4
Release	RL	Surrendering control of an object	Motion case	0–2.0

Table 2 Categorization of five basic hand motions

Motion	OR	AND	NOT
Reach	Upper arm (L/R) Forearm (L/R) Hand (L/R) Finger (L/R)	–	–
Move	Upper arm (L/R) Forearm (L/R) Hand (L/R) Finger (L/R)	*Carry*	–
Position	Hand (L/R) Finger (L/R)	*Carry*	–
Grasp	–	*Carry*	*Carry–*
Release	–	*Carry–*	*Carry*

Note "L" and "R" refer to the left and right sides of the biped model

carrying an object in the current time frame. "*Carry–*", on the other hand, means that the biped was carrying the object in the previous time frame. Table 2 shows the motion identification parameters in the rule-based motion categorization process. Once the motion sequence has been identified, the required motion times are calculated based on the motion–time tables and influencing factors in the MTM-1 system.

3.2 Productivity Analysis

The overall productivity analysis encompasses labour productivity and machine productivity. Given that the present research focuses on manual operations, only labour productivity is computed for the purpose of evaluation. The most common and widely accepted definition of labour productivity in construction is expressed in Eq. 1 [14]. The input requirements for labour productivity computation are the assembly workload (i.e., output) and the corresponding required times. Both the assembly workload and the required times needed to complete the workload can be determined using the automatic motion time analysis. Since standard motion times are used, labour productivity is considered the benchmark that can be used for precise analysis such as simulation, workplace design, and production planning.

$$Labor\ productivity = \frac{Output}{Workhours} \tag{1}$$

3.3 Ergonomic Risk Assessment

In industrialized construction, manual operations may be less physically taxing than in conventional construction, but they are also highly repetitive due to the controlled and standardized nature of factory-based production. Workers are exposed to a high risk of developing WMSDs because they perform tasks involving awkward body postures, forceful exertion, and repetitive motions [16].

REBA and RULA are the two main ergonomic risk assessment tools in construction manufacturing. The primary input requirements of both REBA and RULA are human body postures with joint angles. Muscle use and activity scores are used to evaluate motion repetitiveness in RULA and REBA, respectively. It should be noted that these scores are subjectively adjusted by the analyst based on their knowledge and experience.

In the 3D model, a total of 41 joint angle data points are extracted as the input requirements for the REBA and RULA ergonomic risk computation using the previously developed post-3D ErgoSystem [5]. Although the degree of motion repetitiveness is set up as a user input in the ErgoSystem interface, with the support of the automatic motion time analysis the repetitiveness parameter can be extracted from the 3D model automatically. This innovation of the present research both improves the accuracy of 3D modelling-based ergonomic risk assessment methods and marks an important step toward full automation of ergonomic risk assessment.

4 Experiment

4.1 Experimental Setup

An experiment involving a repetitive reaching motion performed using an optical marker-based motion capture system is conducted as shown in Fig. 2. In the experiment, conducted at the Surgical Simulation Research Lab at the University of Alberta

Fig. 2 Sample frames of reach motion performed in experiment

Fig. 3 Marker placement for experiment

in Edmonton, Canada, an OptiTrack motion capture system with six high-speed cameras is used to capture the kinematics of the body segments with reflective markers attached to the skin at specific body joints. Three male subjects without any injuries are recruited to participate in the experiment, the subjects having heights of 165 cm, 175 cm, and 178 cm, respectively, ages of 23, 23, and 26 years old, respectively, and weights of 68 kg, 75 kg, and 70 kg, respectively. The object to be reached in the experiment is a lightweight cylinder, initially positioned on an elbow-height table in front of the subject.

A total of nine optical markers are used to extract the 3D coordinate information. One optical marker is attached to the top of the lightweight object. Seven optical markers are attached to the arm under observation, as shown in Fig. 3, at the shoulder, upper arm, elbow, lower arm, inner wrist, outer wrist, and middle finger positions. In addition to marker on the object, and the seven markers on the subject's arm, a ninth marker is positioned on the subject's clavicle.

4.2 3D Modelling Data

3ds Max is used to create the 3D biped model and the animation of manual operations. The 3D model is created based on the observation and video recordings of the experiment. Figure 4 shows the initial positions of the biped and object in the 3D model. Given that these are the initial and foundational inputs in the proposed method, the reliability of the motion movements is critical to the accuracy and robustness of the subsequent analysis. The 3D coordinate data from the experiment and the corresponding 3D model are thus compared in order to validate the 3D model simultaneously confirming the reliability of the 3D human motion modelling method proposed in a prior study by authors of the present research [6]. The 3D visualization of the manual operation having been developed, the proposed method is implemented in order to evaluate its performance as a tool for assessing productivity and ergonomics.

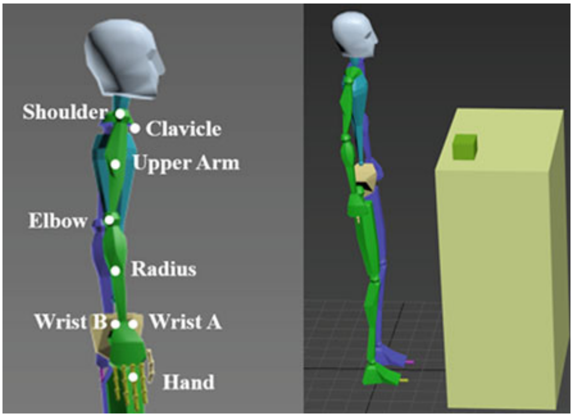


Fig. 4 Initial positions of biped and object in 3D model

In the proposed system, all the basic hand motions are automatically identified, and the corresponding standard motion times are computed, based on the MTM-1 system. The motion–time correction in the 3D model is achieved using MAXScript programming language in 3ds Max. The results of the motion–time auto-correction are the 3D modelling of the manual operation under study and the characterization of a standardized motion–time relationship—outputs that can be used for further posture-based ergonomic risk assessment, production planning and scheduling analysis, and workplace design analysis. Figure 5 shows an example output of the proposed system, where the output text file contains the body segment, the original key frames, and the updated key frames. The original key frames are typically created by the analyst based on experience, whereas the updated key frames are generated automatically based on the proposed system.

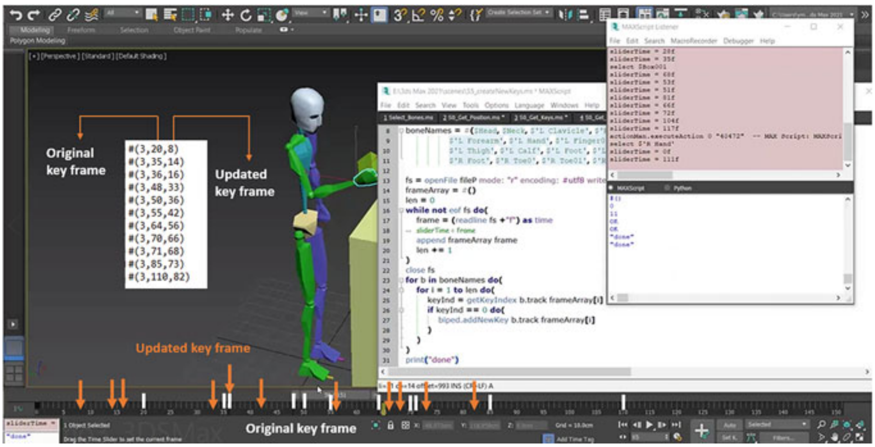


Fig. 5 Original and updated key frames in 3D model

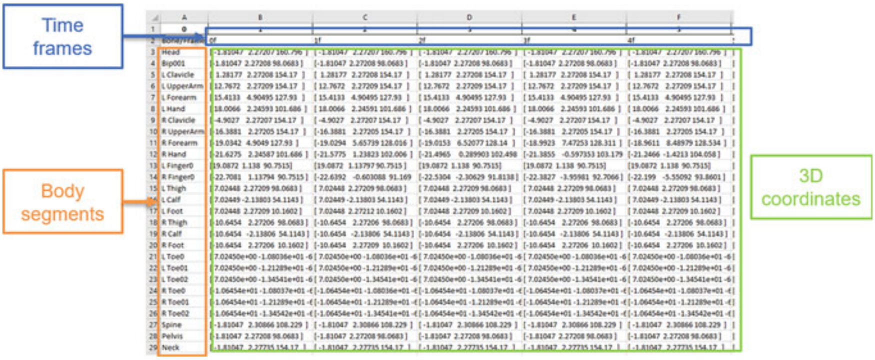


Fig. 6 3D coordinate data at each time frame as extracted from the 3D model

4.3 Productivity Analysis

The key inputs in the productivity analysis are the motion cycle times, which are generated automatically using the proposed method. The 3D coordinates of each bone and of the object at each time frame are extracted from the 3D animation and saved in.csv format, as shown in Fig. 6. Meanwhile, the movements of each body joint between two frames are calculated in order to generate the Boolean table and the distance table that serve the motion categorization process. The motions of both the left and right sides of the body are categorized according to the MTM-1 system. The corresponding time frames are also saved for each basic motion.

The basic motions of reach, grasp, move, position, and release are automatically detected for both the left and right sides of the body. In this example, the cycle time computed for the reach motion is 0.47 s. Thus, the labour productivity of this reach movement is 2.11 units per second according to Eq. 1. The average cycle time in the experiment based on the traditional time study technique is approximately 0.49 s, a result comparable to that computed by the system (thus demonstrating the reliability of the proposed system).

4.4 Ergonomic Risk Assessment

The use of 3D modelling to achieve automated ergonomic risk assessment has been validated in previous studies [5, 6, 17, 18]. The biped data collected from the 3D model are converted to joint angle data as required by the system in order to determine the ergonomic risk ratings based on REBA and RULA. The degree of repetitiveness of motions, meanwhile, is generated as an output of the automatic motion time analysis. The risk score is automatically added if the motion is repeated at least four times per minute, as per the criterion specified in both REBA and RULA. Table 3 compares the original and proposed methods. In this experiment, the average

Table 3 Comparison between original and proposed methods

	Original method	Proposed method
Motion time (s)	0.49	0.47
Productivity (unit/s)	2.04	2.11
REBA risk score	1	2
RULA risk score	2	3
REBA risk level	Negligible	Low risk
RULA risk level	Negligible	Low risk

ergonomic risk score is 2 for REBA and 3 for RULA, meaning that both are in the "low" risk category. However, if the task repetitiveness criterion is not considered, the average ergonomic risk score is 1 for REBA and 2 for RULA, meaning that both are in the "negligible" risk category. This result underscores the fact that accurate input of motion repetitiveness is an essential component of reliable ergonomic risk assessments.

5 Discussion

Construction poses a high ergonomic risk to workers of developing WMSDs, which detract from occupational health and productivity. Given the negative impacts associated with it in terms of both safety and productivity, it is important to accurately evaluate the ergonomic risk of manual operations. The proposed automated ergonomics-based productivity analysis using 3D modelling not only offers benefits in terms of labour productivity analysis, but also improves the accuracy of the ergonomic risk assessment itself. The experimental results validate the accuracy of the required cycle time computation in the proposed system. Moreover, the required cycle time is obtained using the predetermined motion times, which are based on the motion-level analysis. In this regard, the labour productivity metrics obtained using the proposed method can be used as the basis for benchmarking productivity. In other words, by investigating manual operations in industrialized construction, a labour productivity benchmark dataset can be built based on the motion-level analysis described in the proposed method. From an ergonomic health perspective, postures and motions that are both high-risk and easily overlooked can be identified by considering motion repetitiveness, which is taken into account in the proposed method. Because it does not rely on manual input of the motion information, the proposed system also improves upon the post-3D ergonomic analysis system previously developed by authors of the present study in terms of the accuracy of the ergonomic risk results outputted.

The limitations to which the present research is subject, as well as some potential avenues of future research in this area, are outlined below.

- While the present research proves the feasibility of the proposed method with a simple reaching movement, more complex construction tasks must be used to check the accuracy and reliability of the proposed method.
- There are different cases in each motion category in the MTM-1 system. The most common cases are set as the default cases to fully automate the computation process. The automatic identification of the motion cases warrants further investigation.
- Other PMTS methods can be developed and compared in future studies.

6 Conclusion

In intelligent manufacturing, human involvement is still essential, particularly in construction manufacturing. The present research proposes an automated ergonomics-based productivity analysis method for intelligent manufacturing in industrialized construction that merges existing motion time system, ergonomic risk assessment, and 3D modelling techniques. The experiment results demonstrate the feasibility and accuracy of the proposed method. The proposed system is also capable of providing standard motion times with 3D visualization for motion-level productivity measurement. Moreover, the proposed method provides detailed information on postures and their associated cycle times—critical information that helps to improve the accuracy of ergonomic risk assessments. Given that it incorporates 3D modelling, the proposed method can be applied at the work design phase for rapid workplace design and modification in order to reduce ergonomic risk while increasing productivity. The proposed method automatically quantifies the required cycle time and the ergonomic risks associated with body postures during the execution of manual operations in the 3D model, and as such it can facilitate improvements in terms of occupational health and safety, the reliability of planning and scheduling, and the overall productivity of intelligent manufacturing.

Acknowledgements The authors would like to acknowledge Dr. Bin Zheng for the use of the Surgical Simulation Research Lab at the University of Alberta for the motion capture experiment and the volunteers who participated. Special thanks are also extended to Jonathan Tomalty and Kristin Berg for their technical writing assistance. This research was funded by the Natural Sciences and Engineering Research Council of Canada (NSERC) through (File nos. RGPIN-2017-06721, RGPIN-2019-04585, and IRCPJ 419145-15).

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A Web-Based Platform for Real-Time Visualization of Tof UWB Tracking in Construction Sites

Mahdi Naimi Jamal, Tian Jin, and Farnaz Sadeghpour

1 Introduction

Knowing the real-time location of workers and equipment in a construction site can be beneficial for both safety reasons and work efficiency. By knowing the routine routes taken by workers and equipment, the dynamic construction site layout can be optimized to minimize these trips [2]. Also, hazardous areas can be defined which will help to notify workers and prevent them from entering a non-safe area [4]. Another key benefit of knowing the location of workers is to improve the evacuation process. In case of an emergency, if the construction site needs to be evacuated quickly, knowing the location of each worker will help to prevent people from getting stuck or left out in the site [12].

To this end, different locating systems have been developed. These systems fall into two main categories which are vision-based and signal-based [24]. Vision-based systems rely on cameras and computer vision to get the position of people and equipment present in the camera's field of view [24, 29] On the contrary, signal-based methods can locate the person or equipment using the physical principles of the signal in use. Examples of such frameworks are Global Positioning System (GPS), Radio-frequency Identification (RFID), Wi-Fi-based, Bluetooth Low Energy (BLE), and Ultrawide Band (UWB) [1, 24].

For locating assets in an outdoor environment, GPS is the leading technology [1]. However, GPS signals have relatively low penetrability and cannot go through building elements such as walls [28]. Therefore, the need for a robust indoor positioning system (IPS) is present. RFID, Wi-Fi, and BLE perform well in indoor environments but suffer from high error in Non-Line-of-Sight (NLOS) scenarios. UWB on the other hand is more immune to this [6]. Therefore, considering the nature of the

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S. Walbridge et al. (eds.), *Proceedings of the Canadian Society of Civil Engineering Annual Conference 2021*, Lecture Notes in Civil Engineering 247,
https://doi.org/10.1007/978-981-19-0968-9_27

construction sites, and the characteristics of UWB, these systems are gaining more and more attention.

To use UWB, different methodologies have been introduced, including Time Difference of Arrival (TDOA), Angle of Arrival (AOA), Time of Arrival (TOA), and Time of Flight (TOF) [1, 20] Compared to other methods, TOF has a better performance in terms of accuracy and ease of implementation [20]. In the TOF method used in this research, only one listener tag is connected to the computer via wire, while the connection of other tags is wireless. This is a huge benefit for construction sites as it is not always possible to use wires across different parts of a site. The TOF-based UWB RTLS does not require cables for time synchronization thus it will be more cost effective. For traditional TDOA-based UWB, the anchors are significantly more expensive than the tags. As the tags and anchors for this TOF-based UWB RTLS can be utilized interchangeably, there is no specific requirement to distinguish the anchor and the tag modules. Hence, from the economical expense perspective, the TOF-based system is more cost effective. Another key characteristic of a positioning system for a construction site is to be able to monitor the location of assets remotely [21]. To this end, web-based frameworks have been proposed in recent years [14, 17, 23]. In this research, the focus will be on implementing the TOF method to get live locations of assets. As mentioned before, using TOF will ease the implementation process, and having a remotely accessible platform will help with remote monitoring. The proposed system will also be capable of logging all the detected movements. Making the platform available to managers, this logging can be beneficial by providing raw data for further analysis on material and workers' movement which can result in congestion detection, optimization of the construction site layout according to the actual needs [2], as well as safety concerns such as preventing accidents.

2 Literature Review

Real-time locating has various aspects to cover. One of the main components of this practice is data transmission. To achieve a near-live location of an asset, a rapid data transmission with almost no lag is needed. To this end, various approaches have been surveyed.

The first method of data transmission is to connect all anchors through an Ethernet Cable to a computational platform. On a construction site, however, it is not always possible to use wires throughout the construction site. Also, even if possible, this approach is considered inefficient as it results in extra workload regarding the installation and configuration of the anchors [8, 10, 11, 13, 15, 18, 19, 26, 27, 31].

The next method connects the tags to a computer using wireline cables [32]. This method is also not efficient as it demonstrates significant limitations. The most important limitation of this approach is that it is neither practical nor possible, to connect every single worker and equipment with a wireline cable to a computational station.

The third method is to use mobile devices or internet connection for data transmission [16, 22]. The most important aspect of this method is that it enables remote observation of the site data, which as discussed before, has a profound meaning for construction site applications.

Besides the data transmission, another key component of the real-time location visualization platform is the data update rate [9, 25]. To be able to see the location of an asset in each time step, the data refresh rate of the tag and the website should be synchronized.

Different real-time location systems have been developed by various studies in the past two decades [3, 5, 7, 13]. The main function of these developed platforms is to generate alarms when the danger occurs. However, the real-time location presentation is not extensively investigated. As discussed before, real-time visualization can become beneficial. Therefore, this study will investigate the visualization part with the emphasis on real-time presentation. To this end, a web application will be developed which uses only wired tag as a listener. Besides, to gain real-time updates, the refresh rate of the web platform will be the same as the data rate of the tags. Details of how this goal is achieved are discussed in the upcoming part.

3 Methodology

To achieve the aforementioned goal, a TOF-based location tracking system and a web-based visualization are needed. These frameworks will be discussed in the following part.

3.1 *Time-Of-Flight (TOF)*

TOF-based UWB positioning uses the time that the signal needs to travel from an anchor to a tag. Knowing that the signal is traveling with a known speed, referred to as the propagation speed, the distance between a tag and an anchor can be achieved by Eq. 1 [30]:

$$\mathrm{d} = \mathrm{TOF} \cdot \mathrm{c} \tag{1}$$

where d is the distance between the tag and the anchor, TOF is the time that the signal spends traveling, and c is the propagation speed of the signal. To be able to locate an asset in a 2D space, at least three fixed tags are needed.

By having the distance of the asset to each of these tags, the asset's location can be estimated using Eq. 2:

$$\sqrt{(x - x_i)^2 + (y - y_i)^2} = d_i \tag{2}$$

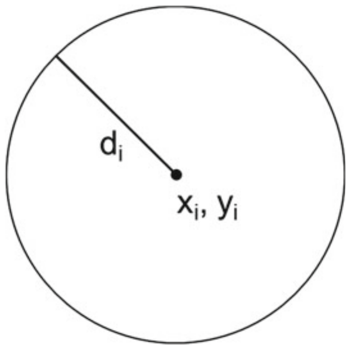


Fig. 1 Estimated location of the tag according to one anchor

where (x, y) is the estimated location of the tag, (x_i, y_i) is the location of anchor i, and d_i is the distance from the tag to anchor i. As shown in Fig. 1, this equation will result in a circle with the center of anchor i and the radius of d_i.

Using the location of the three tags and their relative distance to the asset, the location of the asset can be estimated by solving the system of equations shown below for x and y:

$$\begin{cases} \sqrt{(x-x_1)^2+(y-y_1)^2}=d_1 \\ \sqrt{(x-x_2)^2+(y-y_2)^2}=d_2 \\ \sqrt{(x-x_3)^2+(y-y_3)^2}=d_3 \end{cases} \tag{3}$$

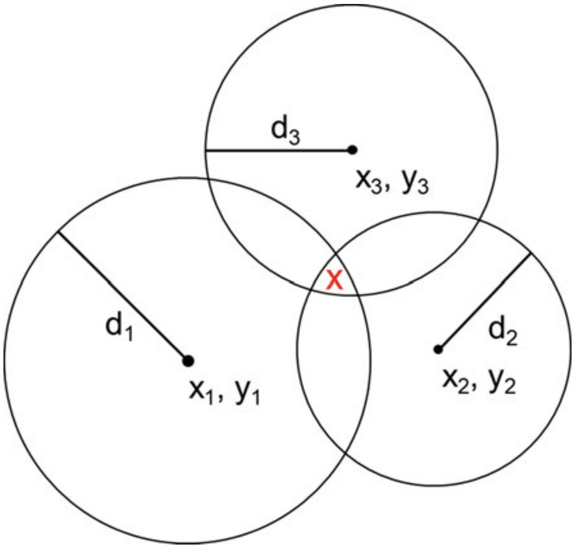
These equations will lead to the intersection of the three circles mentioned above. In case these circles do not intersect in a point, the following system should be solved to obtain the asset's location:

$$\min_{x,y}\begin{cases} \sqrt{(x-x_1)^2+(y-y_1)^2}-d_1 \\ \sqrt{(x-x_2)^2+(y-y_2)^2}-d_2 \\ \sqrt{(x-x_3)^2+(y-y_3)^2}-d_3 \end{cases} \tag{4}$$

Figure 2 shows a visualization of the previous equation. The red cross shows the estimated location, while each circle corresponds to an estimated (x, y) according to each tag.

A similar calculation can be done for 3D using the z component of the location and adding it into the formulas. The only difference between 2 and 3D tracking is that for tracking an asset's location in 3D, at least four anchors are needed. Using ranging data of at least four anchors, the location can be estimated by the same formula using (x, y, z) data as input.

Fig. 2 Estimated location using three tags



3.2 *Web-Based Application*

Using the positioning system mentioned above, location data is gathered. This data contains tag ID, time of reading, and the coordinates. To show this data on the webpage, the data flow is as shown in Fig. 3. The UWB indoor positioning system creates location data and sends it to a teraterm terminal emulator using data cables. Here, the locations will be converted and recorded to a log file format which is then converted into a CSV file. As more methods and functions are available for processing a CSV file, these files are much easier to process compared to the raw data acquired from the sensors. Therefore, instead of using the raw data, the CSV log is passed to the next step. Here, a Flask application written with Python takes the CSV files and hands them over to the JavaScript platform. The data is visualized in JavaScript and handed over to an HTML code to show it on the webpage.

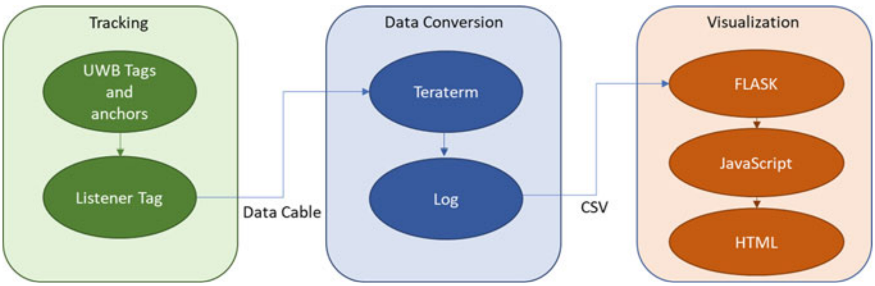


Fig. 3 Visualization of the data flow of the proposed framework

4 Implementation

To implement the mentioned data flow, a webpage is designed to show the plot. This website sends a request, for obtaining a new plot, to the ChartJS function. The request will be directed to the Flask application. To answer this request, the Flask application accesses the latest data, in this case, the last row in the CSV file. This data will be sent back to the ChartJS which will convert the coordinates to a visual plot. The resulting plot will be sent via a push request to the website which results in the website showing the latest location of the tag. To keep this plot up-to-date and obtain the live location, a setInterval() method with the same refresh rate of the tags, in this case, 10 Hz, will be applied. This will result in the website sending requests every 100 ms to refresh the data and consequently receiving the latest location as a response.

Figure 4 shows the resulted sample webpage. The current locations of three tags, that are each assigned to a worker, are visualized using three triangles. As each tag moves, it leaves a transparent trace in the space. This can help with further path analysis, meaning that pathways with the most commute can be known because of their bolder color. Also, points of congestion can be easily detected because they also become bold as time passes and the tag stays at the same place. The console log

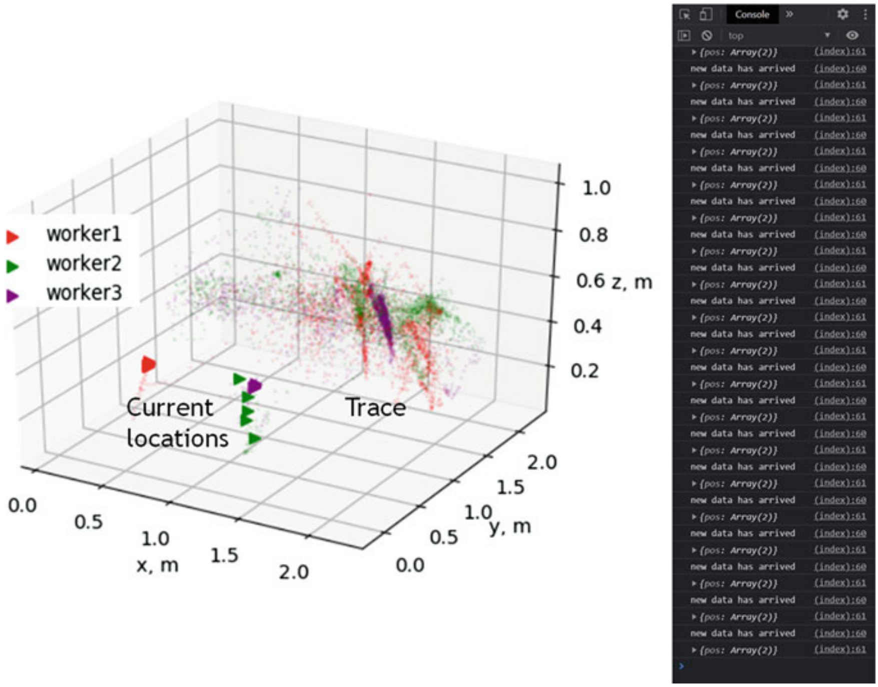


Fig. 4 Screenshot of the website showing the latest position of a tag

of the web browser, in this case, Google Chrome, is also shown to demonstrate the constant input data flow.

5 Summary and Conclusion Remarks

This study developed a platform capable of visualizing the location data in real-time and enabled this conception available for remote access. To this end, the developed web-based platform can show the current location of a tag and stores the historical data. The real-time current locations can be utilized for preventing accidents by visualizing the locations of different labor and equipment on construction sites. The distance between the two tracked objects (such as labor and a piece of running equipment) is indeed important for predicting danger. However, other information such as velocity and movement direction has to be considered. Because a close distance will not trigger injury or fatality hazard if the two objects are moving in two different directions. Different from previously developed platforms, this platform can indicate the direction of the movement, and the approximate velocity of the movement. This will enable the integration of multiple factors while considering the safety hazard.

The preserved historical location estimation data has also profound meaning since it can be utilized for investigations of accidents. Moreover, the historical location estimations can also be utilized to observe the most frequently utilized path for labor and equipment, which can be used for understanding the behaviors on sites. In the future, automation or at least semi-automation on site is an irreversible trend. Understanding the most frequently utilized path on site will also be beneficial for the navigation of the robotics. Remote access to the developed platform also demonstrates unique advantages. Simply by monitoring the construction remotely, the project manager, supervisor, as well as owner will promptly and efficiently understand the progress and situations of construction.

Acknowledgements The authors would like to acknowledge the National Science and Engineering Research Council (NSERC) for the support of this research.

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An Overview of Modeling Spatial Relationships in Site Layout Planning Literature

A. Marcano Pina and F. Sadeghpour

1 Introduction

Site layout planning studies the efficient allocation of temporary facilities in construction sites, a field that has gained increasing interest from researchers in recent years. In this sense, multiple academic journal papers have been published, mainly focused on optimization models to optimize the layout [1–3]. Also, overview papers have studied the different aspects of the problem, directing interest towards time dimension modelling, path planning, objects representation, spatial relationships, and advanced metaheuristics algorithms for problem-solving [4, 5]. One of the essential aspects of construction site layout planning (CSLP) is defining spatial relationships between temporary facilities. Spatial relationships are the logical placement of facilities in the site in relation to each other to achieve planning goals defined for the project.

An example of this can be placing a materials storage facility such that it remains visible from the site office to increase security. Despite the importance of spatial relationships, most studies only consider one (closeness) in the site layout planning model. While utilizing a single spatial relationship simplifies the formulation of the objective function, it can overlook other relationships that are important for placing the facilities on the layout. In former studies, other relationships are used with less frequency but also address different objectives and planning goals [6, 7]. For this reason, the purpose of this overview paper is to present the modeling of the spatial relationships as found in the literature, show examples of applications, and provide recommendations for future work in this area. These findings will facilitate a higher inclusion of spatial relationships in CSLP models, allowing future studies to provide more realistic layouts in correspondence with the requirements of the industry.

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S. Walbridge et al. (eds.), *Proceedings of the Canadian Society of Civil Engineering Annual Conference 2021*, Lecture Notes in Civil Engineering 247,
https://doi.org/10.1007/978-981-19-0968-9_28

Fig. 1 Classification of journal papers in site layout planning research

2 Methodology

This review paper is based on 87 studies published between 1994 and June 2020, which were found using four research databases: Scopus, Science Direct, and Google Scholar. The search was narrowed using keywords such as "site layout planning", "construction site", and "temporary facilities allocation". Other studies were selected through cross-referencing from the bibliography of each paper. Based on this review, various aspects of the site layout planning problem were identified and classified into four main categories as shown in Fig. 1: optimization models, decision-support systems, software integrated models and overview papers.

After classifying the studies, it was found that only the papers presenting optimization models contained information regarding spatial relationships, mathematical formulation and application examples; in contrast, the rest of the categories focused on showing other aspects of the problem. The optimization models were selected as inclusion criteria resulting in 66 papers. The objectives, objective functions, planning goals and spatial relationships were identified either within the mathematical formulation of the model, the problem description or through examples and case studies presented by researchers. However, In reviewing the papers, it was found that planning goals, objectives and spatial relationships terms were commonly confused or used interchangeably, suggesting that clarification of each term is required.

3 Planning Goals, Objectives, Objective Function and Spatial Relationships

Planning goals were found in examples as improving productivity, safety, security, and functionality in the site. Objectives seek to satisfy a specific requirement, for example, ensuring visibility from the site office to the materials storage area, which is translated into an objective function. Finally, spatial relationships support the satisfaction of objectives and include closeness, farness, minimum and maximum distance, adjacency, containment, mutually exclusive relationships, orientation, and visibility. However, these terms are commonly confused or used interchangeably; hence, this section intends to illustrate the differences between the aforementioned concepts to create a unified understanding.

3.1 Planning Goal

As found in the literature, there are 4 general goals that have been expressed for a site layout plan: to increase productivity, functionality, security, or safety. Goals are translated into objectives, such as minimize the distance between temporary facilities with high levels of interaction. Objectives typically involve spatial relationships and are translated into the objective function to quantify them to be used in optimization models. An example of this can be placing the carpentry shop near the building in construction, which will minimize the distance between them (objective) to increase productivity in the construction site (planning goal). By applying closeness as spatial relationship, the objective is translated into the objective function. Definitions and examples of this aspect include:

- Increasing productivity: this goal seeks to improve the efficiency of construction activities, given by the ratio between the time spent working and the unproductive time due to time spent in movements across the site (distances). To achieve this goal, some examples in the literature have minimized the weighted distance in the objective function following the prioritized relationships between temporary facilities [8].
- Increasing safety: this seeks to reduce the accident probabilities in construction sites. Examples of this goal have been presented in the literature by placing concrete batching plants far from site offices [9] or by providing a minimum distance between site offices and cranes [1].
- Increasing security: through specific measures taken to protect people, equipment, or materials in the site from theft or violence. An example of this is to place material storage facilities within the visibility area from a guardhouse, increasing visibility and security in the area.
- Functionality: the use of one temporary facility or construction object is required for the operation of another object. An example of functionality can be the application of proximity of a gas-powered heater and a propane tank [10].

3.2 Objective

The objectives are the numerical translation of planning goals to be used in objective functions, which frequently involve spatial relationships between temporary facilities. For example, to increase productivity (planning goal), the model will minimize the distance between the temporary facilities (objective) using spatial relationships, such as closeness or adjacency. In the literature, objectives are used to address one or multiple planning goals and can also be impacted by one or more spatial relationships. Table 1 illustrates examples of different objectives, goals, and spatial relationships. As can be seen in the examples, an objective can help achieve one or more planning goals. For instance, minimizing the distance between the materials hoist and the guardhouse can help increase security in the site. This can alternatively be achieved by ensuring visibility from the former to the latter. Another example is minimizing the distance between the steel storage and the electrical shop, which increases productivity, and helps address the functionality requirement since one facility supplies materials to the other.

From the examples in Table 1 can be inferred that the relationships between temporary facilities can have different representations in the site layout. In this sense, Fig. 2 shows six schematic examples of spatial relationships applied to temporary facilities: (a) closeness, (b) farness, (c) containment, (d) minimum distance, (e) maximum distance, and (f) visibility.

Figure 2a shows the placement of a site office as close as possible to the labor residence, which minimizes the distance between them and increases productivity in the site. As demonstrated with farness in Fig. 2b, the site office is located as far as possible from the welding shop to avoid risks, which is also applicable to areas allocating hazardous materials such as diesel, oil, or solvents. Figure 2c demonstrates

Table 1 Examples of goals, objectives, and spatial relationships

Planning goal	Objective	Spatial relationship	Example
Productivity	Minimize the distance	Closeness	Supply points and tower cranes should be placed as close as possible
Safety	Maximize the distance	Farness	The site office should be far from the welding shop
Security	Direct observation/minimize the distance	Visibility	The materials hoist should be visible from the guardhouse
Functionality	Minimize the distance	Adjacency	The steel storage area should be placed next to the electrical shop

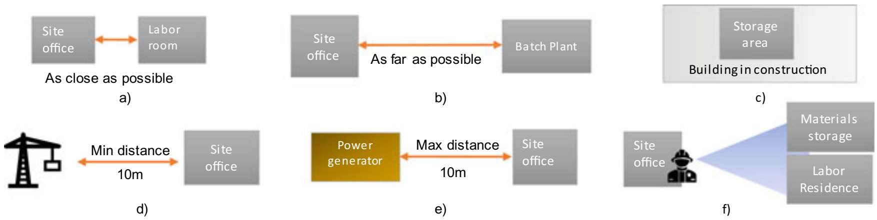

Fig. 2 Schematic examples of spatial relationships: **a** closeness, **b** farness, **c** containment, **d** minimum distance, **e** maximum distance, and **f** visibility

how allocating a storage facility inside the building in construction reduces the travel movement of employees, materials, and equipment. Figure 2d illustrates a minimum distance between the cranes and other temporary facilities, which increases safety in lifting operations. This can also be considered within exclusion zones for the same purpose.

On the other hand, Fig. 2e shows the assignment of a maximum distance of 10 m between the site office and a power generator to guarantee functionality within a safety distance from employees. Finally, Fig. 2f depicts visibility from a site office to a materials storage facility and a labor residence. This placement can be required to increase the security of construction materials and productivity through the supervision of employees in the residence.

As explained through the examples, multiple objectives can address a goal and conversely, a goal can be represented through more than one objective. This is demonstrated through objective functions used in single or multi-objective optimization.

3.3 *Objective Function*

In optimization models, an objective function (also referred to as utility function) is applied to improve the layout, where its mathematical formulation represents the objective(s) defined for the problem. For example, in a single optimization model where the goal is to increase productivity in the site, this goal is translated into the objective of minimizing the distance between the temporary facilities. This can be represented by an objective function (OF), such as Eq. 1, given by the minimum value of the weighted distance, Min OF:

$$Min\ OF = \sum W_{ij} * D_{ij} \tag{1}$$

here, W_{ij} and D_{ij} are the level of importance given to the interaction and the distance between facilities *i* and *j*, respectively.

Multi-objective optimization typically shows contradictory goals and objectives, such as increasing productivity and reducing risks, addressed through distance minimization and/or maximization. In this case, two or more objective functions exist simultaneously, making it challenging to get a single optimal solution. Researchers commonly assign an importance weight to each function to prioritize one objective over the other(s) and obtain the best result possible [11], 2 For example, Eqs. 2 and 3 define the objectives of increasing productivity (f_1) and safety (f_2), and Eq. 4 is the weighted sum of both functions, F, based on the importance value assigned to each objective:

$$f_1 = Min \sum W_{ij} * D_{ij} \tag{2}$$

$$f_2 = Max \sum R_{ij} * D_{ij} \tag{3}$$

$$F = w_1 * f_1 + w_2 * f_2 \tag{4}$$

here, W_{ij}, R_{ij}, and D_{ij} are the importance of closeness, importance value of farness, and the distance between temporary facilities *i* and *j*, respectively. Also, w_1 and w_2 represent the weights associated with functions f_1 and f_2, respectively.

3.4 Spatial Relationship

In site layout optimization, the objectives commonly involve spatial relationships between temporary facilities. In the examples mentioned in Table 1, the objectives of minimizing and maximizing distance introduced closeness and farness relationships between facilities. Multiple optimization models have used closeness to achieve these objectives, but other spatial relationships can also contribute to this purpose. In this sense, eight spatial relationships were found in the literature in the mathematical formulation of the model, the problem description, or examples and case studies. Figure 3 shows the spatial relationships distribution in optimization models. Figure 3a presents the frequency of each spatial relationship in different studies. It can be seen that the most used relationship is *closeness*, followed by *farness*, *minimum, and maximum distance*. There were also applications of *containment*, *exclusion zones*, *adjacency*, *orientation,* and *visibility*. Figure 3b shows different combinations (or applications) of spatial relationships in optimization models. 28 studies had only one spatial relationship, followed by two and three relationships with less frequency. Only four case studies with four or more spatial relationships were found. The definition and examples of each spatial relationship are described in the next section.

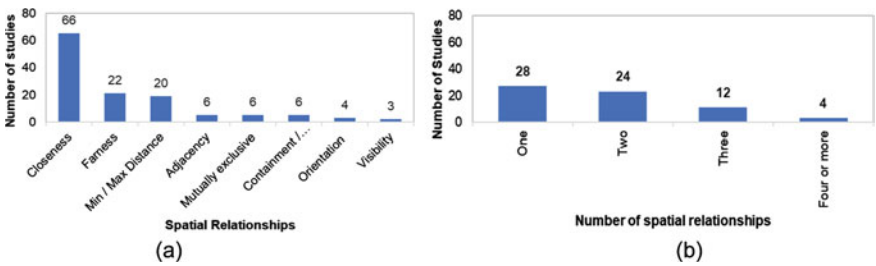

Fig. 3 **a** Distribution of use of various spatial relationships in the literature, **b** number of spatial relationships used in CSLP models

Closeness

Closeness refers to placing temporary facilities as close as possible. This spatial relationship was found to be the most used in the literature (Fig. 3a). To assign an importance value to the distance between temporary facilities, examples of *closeness* have been presented as the cost of the workflow [8], employees' or materials' travel frequency [2, 12] and travel costs [13]. As seen in the literature, the higher the value for closeness in the objective function, the more important is the relationship between temporary facilities. Equation 5 presents an example formula to minimize the distance between facilities given by Min $f_{(X)}$:

$$Min\ f_{(X)} = W * \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2} \tag{5}$$

where W is the value of *closeness,* x_i, y_i are the coordinates of facility *i*, and x_j,y_j are the x,y coordinates of facility *j*. Figure 2a shows a schematic example of this relationship.

Farness

Farness aims to place temporary facilities as far as possible. Applications of this relationship represented it as a negative or very low positive value [14, 15]. For example, if a concrete batching plant must be placed far from the site office to increase safety, *farness* is applied by maximizing the distance between the facilities (Fig. 2b). Equation 6 shows a typical mathematical expression that helps achieve this objective given by Max $f_{(X)}$:

$$Maxf_{(X)} = W * \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2} \tag{6}$$

where W is the value of farness, and xi, xj, yi, yj are the x,y coordinates of the temporary facilities in the site layout, respectively.

Minimum Distance

The *minimum distance* is used to place the temporary facilities within a specific separation distance, not lower than the value decided by the user. In applications from the literature, this spatial relationship helped increase safety in the site. Figure 2d shows the use of this relationship to place tower cranes within a safe distance from the site office, which can also be applied to allocate facilities containing dangerous materials [16, 17]. Equation 7 shows an example of this function, given by D_{min} as the *minimum distance* allowed:

$$D_{min} \leq \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2} \tag{7}$$

where x_i, y_i, x_j, y_j are the x and y coordinates of facilities *i*, and *j* respectively.

Maximum Distance

Maximum distance demands a specific separation distance assigned by the user, which can not be less than the actual distance between the facilities. The utilization of this spatial relationship was present in problems where crane and supply points had to be placed within a maximum distance [1, 18]. In addition, this relationship can also be applied to ensure functionality between power generators and site offices while maintaining a safe distance (Fig. 2e). Equation 8 shows an example of a mathematical formulation given by D_{max} as the *maximum distance* allowed between temporary facilities:

$$D_{max} \geq \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2} \quad (8)$$

where x_i, y_i, x_j, y_j are the x,y coordinates of facilities i, and *j,* respectively.

Adjacency

A*djacency* involves the placement of two facilities right next to each other. Applications of this relationship were mathematically formulated [7], presented as binary constraints [15] or corner to corner relations [19]. An example from the literature placed a storage area adjacent to the garage to facilitate materials allocation in the site, increasing productivity. Still, this relationship can also help with safety, security, and functionality. Equation 9 shows an example of the mathematical formulation given by XO_j, $XO_{j+1,}$ YO, YO_{j+1} as the X, Y coordinates of the centroid of the facilities:

$$\begin{aligned} XO_j - XO_{j+1} &= \frac{b_j}{2} + \frac{b_{j+1}}{2} \\ YO_j - YO_{j+1} &= 0 \end{aligned} \quad (9)$$

where b_j, and b_{j+1} are the width of the facilities.

Containment

C*ontainment* refers to placing an object inside an area delineated by the boundaries of another area [5]. An example of this spatial relationship was illustrated by placing a materials storage area inside the building in construction (Fig. 2c). As found in the literature, researchers have presented containment as rules in the model [19, 20] or through mathematical formulation [6]. Equation 10 shows an example formulation given by the net space available $A_{i,t}$:

$$A_{i,t} = G_{i,t} - C_{i,t} - \sum (FO_{i,t} - FP_{i,t}) \quad (10)$$

where $G_{i,t}$ is the gross floor area, $C_{i,t}$ is the clear area required, $FO_{i,t}$ is the floor space occupied by an activity, and FP_it is the reduction in floor space after floor partitioning i at time t (dynamic site layout).

Mutual Exclusion

The mutual exclusion relationship prevents a specific temporary facility from being placed in the same area where other facilities are placed. Examples in the literature show how tower cranes can not be placed in the same area as site offices [1]. This relationship is illustrated through the example formula in Eq. 11 and given by the binary variable λ_{ij}:

$$\lambda_{ij} + \lambda_{ij+1} \leq 1 \tag{11}$$

where $\lambda_{ij} + \lambda_{ij+1}$ prevents two different facilities from being placed in the same area by forcing one of them to have a value equal to zero.

Orientation

An *orientation* relationship between temporary facilities forces them to be located at a specific angle or in the north, south, east, or west from another facility. Only four applications of this relationship were found in the literature (Fig. 3a). An example mathematical formulation from the literature is illustrated through Eq. 12 [21], where the objects are rotated around their centroids. This is given by the centroids x_i, y_i of the facility:

$$\begin{aligned} x_i &= \left[(x - x_c) * cos_{(\theta)}\right] - \left[(y - y_c) * sin_{(\theta)}\right] + x_c \\ y_i &= \left[(x - x_c) * cos_{(\theta)}\right] - \left[(y - y_c) * cos_{(\theta)}\right] + y_c \end{aligned} \tag{12}$$

where x_c, x, y_i, y_c, are the x, y coordinates of the centroid of the facility, and Θ is the rotational angle required by the orientation spatial relationship.

Visibility

Visibility refers to the direct observation from a facility to specific locations in the site (Fig. 2f). *Visibility* has been applied in the literature to place material hoists in line of sight of the site offices and/or security gate [22]. An example formulation is presented in Eq. 13 [7], given by the x,y coordinates of the facilities represented as XO_j, X_c, X, YO_j, Y_c:

$$\begin{aligned} \frac{(YO_j - Y_{c)}}{(XO_j - X_{c)}} &\geq S_{min} \\ \frac{(YO_j - Y_{c)}}{(XO_j - X_{c)}} &\leq S_{max} \end{aligned} \tag{13}$$

where S_{min} and S_{max} are the minimum and maximum slopes of the visibility area within which the facility should lie.

3.5 An Illustrative Example

As mentioned in the previous sections, it is important to highlight the difference between goals, objectives, and spatial relationships due to the common confusion on the terminology. To illustrate this difference with an example, suppose that the *planning goal* seeks to improve safety conditions on the site. Areas where dangerous activities are taking place, such as welding shops, must be placed as far as possible from working areas such as site offices; hence, the *objective* is to maximize the distance between the welding shop and the site office. This objective can be achieved by applying a farness *spatial relationship* between these temporary facilities. The objective function in Eq. 14 shows an example of the mathematical formulation of this objective, given by Max $f_{(X)}$:

$$Maxf_{(X)} = W * \sqrt{\left(x_i - x_j\right)^2 + \left(y_i - y_j\right)^2} \tag{14}$$

where W is the value of importance or weight of farness, and x_i, y_i, x_j, y_j are the x,y coordinates of the site office and the welding shop, respectively.

4 The Importance of Modeling Spatial Relationships In Site Layout Planning

The application of spatial relationships in the site layout contributes to addressing important planning goals, such as productivity, safety, security, and functionality. In this sense, Fig. 4 shows the utilization of adjacency, visibility, closeness, farness, and minimum distance to the temporary facilities. The site office is adjacent to the labor residence to increase productivity through distance minimization. At the same time, these two facilities are placed as far as possible from the construction area to increase safety to employees, which is also addressed by placing the power generator within a minimum distance of 10 m. The materials storage area is placed close to supply points and the building in construction but is also visible from the main gate where security personnel has direct observation, which seeks to increase productivity, functionality, and security, respectively. As can be seen, the layout presents a logical allocation of the facilities in correspondence with planning goals and objectives.

A CSLP model able to address multiple spatial relationships can provide flexibility in the nature and number of requirements needed by the problem; however, more computational effort could be required, presenting an optimization decision that researchers should evaluate. In future works, this dimension can introduce additional methods to model and solve the construction site layout planning problem while considering the complex and dynamic aspects that this problem entails. Finally, understanding the importance of the interaction between goals, objectives and spatial

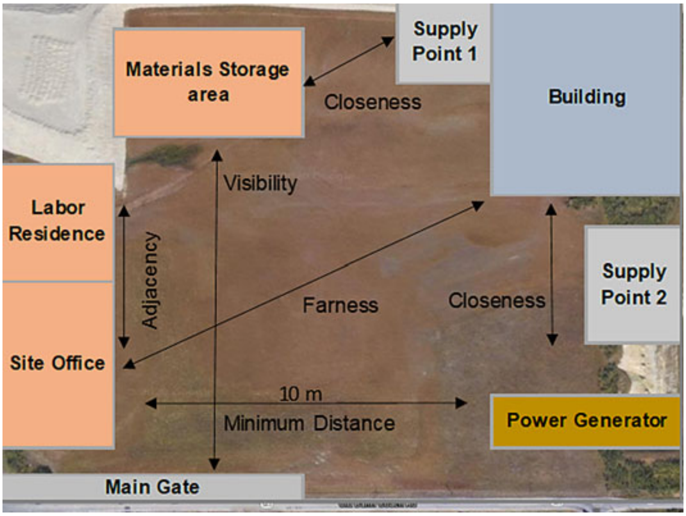

Fig. 4 Spatial relationships modelling in the construction site layout

relationships in optimization models can open the door to developing efficient techniques for everyday utilization in construction sites.

5 Summary and Concluding Remarks

The study presented spatial relationships and their applications in CSLP problems based on 87 formerly published academic journal papers. Out of these, 66 optimization models included closeness as a spatial relationship and 40 papers used more than one spatial relationship. Additionally, this review allowed identifying planning goals and objectives for site layout planning commonly used in literature. Examples of definitions and mathematical formulation of each spatial relationship have been presented, followed by their graphical representation and application in construction sites. The results show that multiple optimization models had been developed in the field, using one spatial relationship.

Nevertheless, some studies included other spatial relationships to address different goals and objectives, which shows an increased interest in understanding this dimension. However, there is still a gap in the inclusion of spatial relationships in optimization models, which presents a research opportunity for future studies. The findings of this study presented the following spatial relationships: *closeness, farness, minimum and maximum distances, mutually exclusive relationships, adjacency, visibility, orientation, and containment*. In addition, the results show productivity, functionality, safety, and security as planning goals. Finally, example objectives include minimizing distance, maximizing visibility, and ensuring a minimum distance.

Understanding how spatial relationships help achieve planning goals while solving the CSLP problem can open the door to include this aspect in future works. As presented in this study, the efficient integration of spatial relationships in CSLP optimization models can contribute to more realistic site layouts. Also, expanding the knowledge about specific requirements and needs from the industry can increase the application of optimization models in real-life construction projects. Given the complex and dynamic nature of construction sites, each problem is unique, with different sets of constraints and specifications. However, spatial relationships represent a practical tool that can help solve a broad range of CSLP problems.

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Virtual Reality-Motion Capture-Based Ergonomic Risk Assessment of Workstation Designs of Construction Manufacturing Facilities

R. Dias Barkokebas, M. Al-Hussein, and X. Li

1 Introduction

In offsite construction, 60–90% of the tasks conventionally performed on-site are instead performed in a factory [17]. Although workers benefit from the factory environment and from the utilization of automated or semi-automated equipment, they are still exposed to high degree of physical demands [20]. For instance, repetitive motion, which is frequently observed in construction manufacturing tasks due to the standardization of products, intensifies muscular tension even if awkward body posture is not required and force level is low [20]. In fact, forceful exertion, awkward body posture, and repetitive motions are the primary causes of work-related musculoskeletal disorders (WMSDs) [6], which often result in a loss of productivity attributable to higher absenteeism, injury rates, and early retirement [5]. As processes are centralized in workstations on the production line, the extent of worker exposure to the risk of WMSDs is largely a function of workstation design and facility layout. As stated by Deros et al. [8], a workstation designed by taking ergonomics into account not only guarantees the health and safety of workers but also increases the productivity of the production line. However, although ergonomic principles are implemented during the design of workstations, workers can still be exposed to ergonomic risks due to mismatching anthropometry data during the workstation design [21] and operational factors such as process flow and task repetition [12]. Hence, assessing ergonomic risks of workstations is needed to provide a safer workplace and reduce long-term exposure of workers to the risks associated with WMSDs.

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S. Walbridge et al. (eds.), *Proceedings of the Canadian Society of Civil Engineering Annual Conference 2021*, Lecture Notes in Civil Engineering 247,
https://doi.org/10.1007/978-981-19-0968-9_29

Traditionally, ergonomic analyses of workplaces are conducted by observing workers on the production line. However, this manual observation requires an ergonomist or a field specialist, is laborious, and error prone due to observer bias and occlusion issues [13]. Furthermore, any alteration to workstation design is reactive resulting in productivity losses and increased time and cost of implementation [19]. To overcome these limitations, one of the most effective approaches to control the degree to which workers are exposed to the risk of developing WMSDs is to identify and prevent ergonomic risks in early design stages by using conventional physical prototypes. However, physical prototyping requires the commitment of major resources [2].

Simulation and using virtual models of work scenarios are both powerful approaches to achieve a robust analysis of human-product interactions at any stage of design development [18]. In particular, virtual reality (VR) produces immersive computer-generated virtual environments in which users can experience and provide insights on situations/products found in the real-world [22]. VR enables users to review designs based on interactions at a real scale, which is a primary benefit of physical prototyping, by allowing users to experiment and evaluate prototypes in a realistic manner [23]. In addition, adjustments to the design of a workstation can be easily incorporated as an updated design can be quickly re-evaluated in the VR environment. Therefore, VR aids in the decision-making process by adding speed and flexibility to the design development phase. The application of VR in the construction industry is explored in a variety of areas such as engineering and architectural design review [25], training of workers to use construction equipment and do new tasks [3, 15], and ergonomic analysis [4, 9, 10]. However, according to a systematic review on the subject, research is still needed to realize the full potential of the implementation of VR in the architecture, engineering, and construction sectors [7]. In order to evaluate two design options proposed for a workstation at which hardware is installed on a window frame, the present study applies a VR-based simulation method to proactively identify ergonomic risks based on body motion data collected using an inertia motion capture (MOCAP) system.

2 Methodology

The present study aims to explore the application of a VR-MOCAP–based ergonomic risk assessment method to identify ergonomic risks associated with tasks performed at a workstation during the design phase in order to facilitate selecting the workstation with lesser ergonomic risks for further design development and to identify potential design improvements. It is important to mention that this research is an extension of the study conducted by Barkokebas and Li [9] that proposes a VR-based ergonomic risk assessment method to identify ergonomic risk ratings proactively in the initial phase of workstation design. Another layer of complexity and accuracy is added to the method proposed in [9] in that the present study incorporates the utilization of an inertia MOCAP system to collect body motion data.

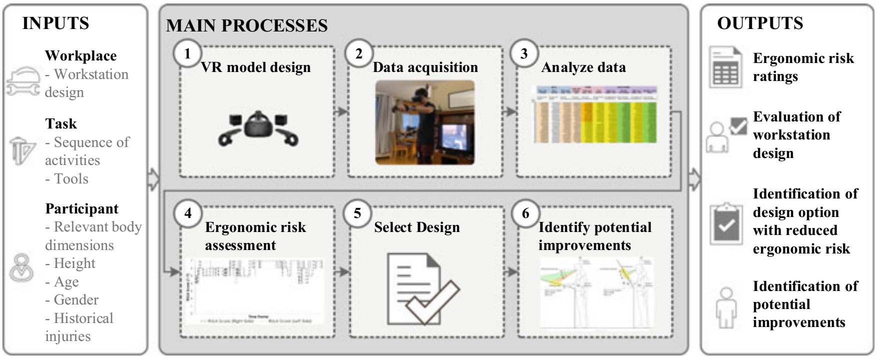


Fig. 1 Overview of research methodology

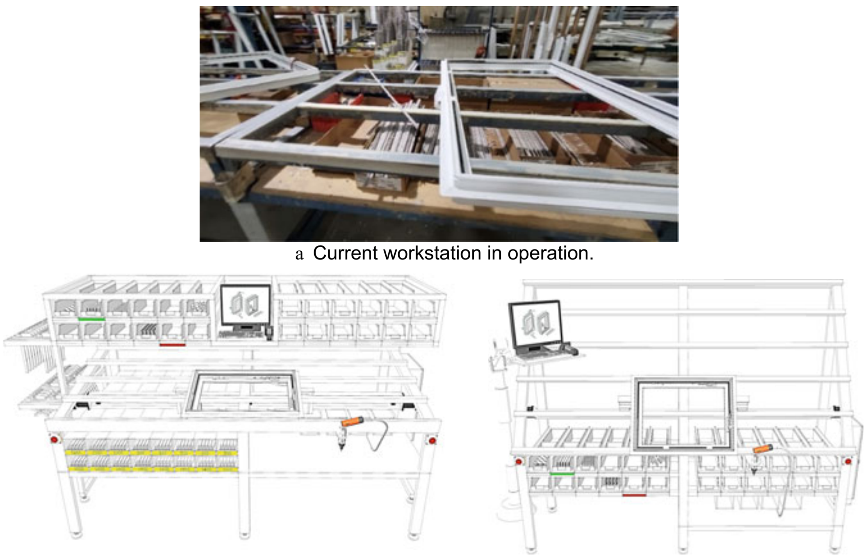
The methodology followed in the present study comprises six steps as illustrated in Fig. 1. The inputs of the methodology include the following: participants' height, age, gender, relevant body dimensions, and historical injuries that may affect participant's mobility; information pertaining to the task to be simulated, such as workstation design and dimensions, sequence of activities, and corresponding tools/procedures; and the results of two assessment methods, Rapid Entire Body Assessment (REBA) and Rapid Upper Limb Assessment (RULA). In step one, a VR application is designed to simulate a task performed at a construction manufacturing facility. Unreal Engine is chosen to create this application due to its capabilities of utilizing Blueprint Visual Scripting to develop realistic virtual environments. In step two, research experiments are conducted in the VR environment to acquire information on human body motions. Participants, researchers at the University of Alberta, are invited to participate in the experiment voluntarily. In step three, body motion data is analyzed to check for outliers and inconsistences. Then, in step four, relevant body joint angles are retrieved from the body motion data and inserted as input in a pre-structured Excel spreadsheet from which ergonomic risk ratings are calculated using two existent risk assessment methods, REBA and RULA. The force and load on the body are estimated based on the weight of objects being handled. After rating the ergonomic risks of the investigated task, the total rating of the task and the rating of each body segment are compared for the two design options being explored. To account for the variance between the time required to complete the task in each design option, the average REBA and RULA rating and the percentage of median time spent at each risk range is determined and applied as a decision factor in the analysis. In addition, the maximum and minimum REBA and RULA ratings are verified to assess if a design option exposes users to higher range risks than the other. Based on these factors, a design option is selected in step five. In terms of further reducing postural-based ergonomic risks, areas of potential design improvements are identified in step six.

3 Case Study

Two design options are selected for a workstation at which hardware is installed on a window frame. These design options and the current workstation that is in operation are shown in Fig. 2. The tasks performed at this workstation include picking up hardware from the shelves and placing hardware in the correct location on the window frame, attaching hardware to the frame using screws and a wireless compact drill driver, lifting and rotating a 1.62 kg, 35 × 40 cm rectangular window frame, and picking and placing the operator (a larger hardware piece) on the window frame. The task is analyzed as a continuous operational process for the purpose of ergonomic risk ratings. The experiment is carried out with participants who complete the task in the VR environment in an unobstructed area measuring 1.80 × 2.40 m, which encompasses a play area of 1.50 × 2.10 m in the VR environment.

3.1 Virtual Reality Environment

The VR environment is composed of a manufacturing facility in which the two design options being investigated are virtually represented at full scale according to their design specifications. When the participant engages in the VR environment, a window frame measuring 35 × 40 cm has already been placed on the work surface of the workstation and pieces of hardware similar to the real-world ones are located



a Current workstation in operation.

b Design A.

c Design B.

Fig. 2 Current workstation design and the two design options under study in storage bins placed on shelves as specified in the design drawings. While the user is immersed in the virtual environment, the participant can interact with the virtual workstation and engage in movements such as picking up, holding, and attaching pieces of hardware to the window frame, as well as hold and rotate the window frame. The VR environment is designed in such a manner that in order to hold a piece of equipment, the participant must keep pressing the side buttons of the hand controller; this is done to ensure that participants distinguish the motion of holding an object in the virtual environment from other motions (for instance, touching an object). It is important to mention that all pieces of material/equipment lifted in the real-world weigh less than 2 kg, thus their weight does not have an impact on either the REBA or RULA analyses. The approach followed in Dias Barkokebas and Li [9] to develop a VR application for ergonomic studies has been applied during the design phase of the VR application developed for the present study.

3.2 Participants

Participants with no history of musculoskeletal injuries are selected to represent various percentiles of the population in the United States according to their stature [1]. This approach is chosen as it has been previously applied in a similar study [19] and is recommended to overcome limited information about end-users during the design phase [11]. Before participating in the experiment, participants are given information about the present study and about the task to be performed (i.e., what is needed to be done and how to operate the provided tool). In addition, participants are asked to read and sign a form consenting to participating in this research and appearing in photo and video data collected during the experiments. Once all instructions are given and questions are addressed, the 17 inertia inertial measurements units (IMUs) are placed on participants' body segments. Altogether, four participants participated in this study; Table 1 provides participant information relevant to the present study.

Table 1 Characteristics of participants

ID number	Gender	Age	Weight (kg)	Height (cm)	Percentile	Historical injury
1	Male	26	65	175	50th	No
2	Female	31	54	163	50th	No
3	Male	29	78	187	95th	No
4	Female	30	62	171	95th	No

3.3 Data Collection and Analysis

Body motion data are collected using an inertia MOCAP system, the Xsens MTN Awinda, which consists of 17 IMUs, a wireless station receiver, motion track full body Velcro straps (including shirts, headbands, footpads, and pairs of gloves), and one segmometer. Figure 3 shows a participant wearing the inertia sensors. To estimate body motions accurately, participants' height, foot length, arm span, ankle height, hip height and width, knee height, shoulder height and width, and shoe sole height are inputted in the Xsens MVN Analyze 2020.0 software. The abovementioned MOCAP system is calibrated for each participant prior to starting the experiment. To perform this sensor-to-segment calibration, each participant is asked to stand in a known pose (i.e., neutral pose) and to complete a known motion (i.e., walking back and forth in a straight line). The calibration is only accepted if its estimated quality is indicated as "good", the highest level of calibration quality in the software. In addition to the MOCAP system, video cameras are also used to record videos during the experiment to assist in the event of inconsistent data from the sensors.

Once the research experiment is concluded, the raw data are extracted using the software. The data contains information on 66 joint angles, including horizontal and vertical axes, and its output frame rate is 60 Hz. After cleaning and analyzing the data to check for inconsistencies, only information relevant to both REBA and RULA methods is retrieved. During the data analysis, left and right sides, rotation, lateral bending, twisting, and arm movements across the body midline or out of the body line are identified and evaluated separately.

As mentioned in Sect. 2, ergonomic risk ratings are identified using REBA and RULA, which are frequently applied in research studies as they accurately provide a qualitative risk level based on a quantitative rating as follows: for RULA, 1–2 = negligible, 3–4 = low, 5–6 = medium, and 6 + = very high [16]; while for REBA,

Fig. 3 Participant (ID 1) with inertia MOCAP sensors

1 = negligible, 2–3 = low, 4–7 = medium, 8–10 = high, and 11–15 = very high [14]. REBA and RULA ratings, total risk rating and risk rating of each body segment for a continuous operation process, are calculated based on the data retrieved from the MOCAP system. Calculating the risk rating for each body segment facilitates a complete and thorough analysis of the task and the identification of body segments that are subjected to a high degree of physical demand, and, therefore, have a high risk rating; this in turn aids in the identification of potential improvements to the workstation designs under study.

4 Results

The results indicate that both design options need further investigation to determine which design changes could be implemented to reduce ergonomic risks as per the interpretation of both the RULA and REBA scores shown in Fig. 4. In general, RULA scores ranging from 5 to 6 indicate that further investigation is needed, and changes should be made soon, while a RULA score of 7 indicates that changes should be implemented; REBA scores ranging from 4 to 7 indicate that the risk is medium and that the workstation design should change soon, while REBA scores ranging from 8 to 10 represent high risk and thus changes should be implemented. With respect to Fig. 4, considering the percentage of median time that participants spent in each risk range during the task, participants spent less time in a high-risk range in Design B. This finding is also confirmed by verifying the average total risk rating obtained by each participant in both design options. As noted in Fig. 5, the average total risk rating for all participants in Design A is 7 and 8 for RULA and

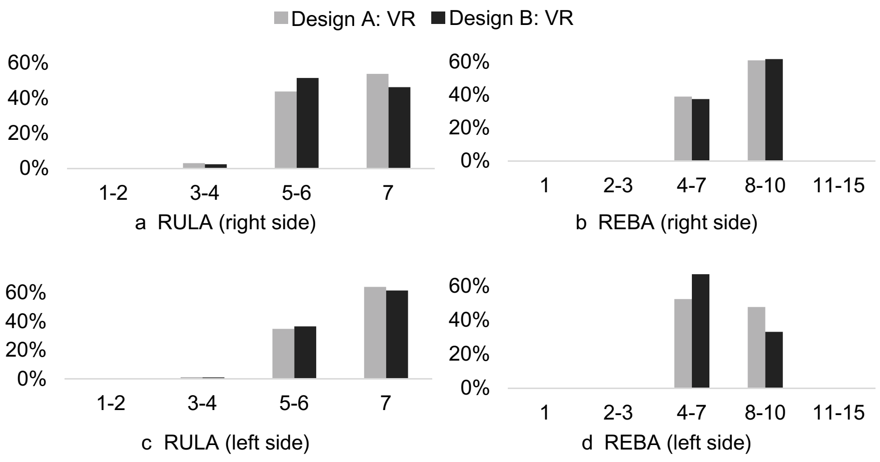


Fig. 4 Percentage of median time spent at each risk range during the task in design options ($N = 4$)

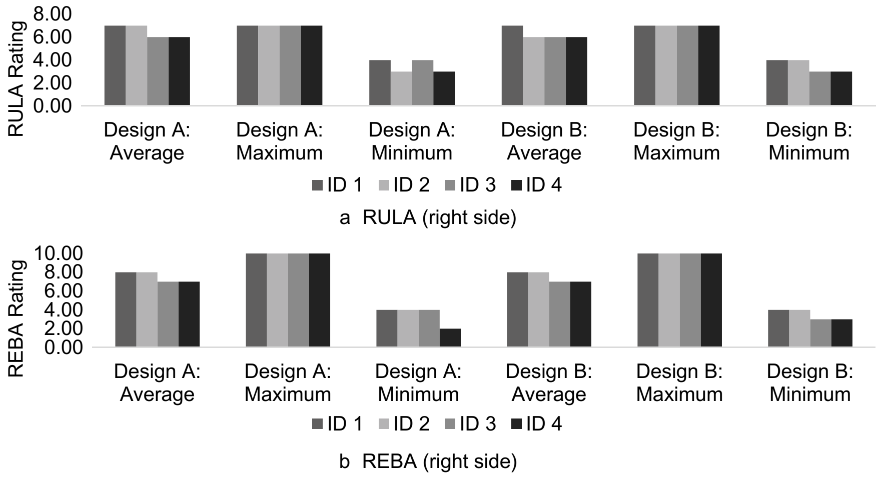


Fig. 5 Total risk rating for a continuous operation process ($N = 4$)

REBA, respectively; while the average for Design B is 6 and 8 for RULA and REBA, respectively. When analyzing the highest and lowest total ratings faced by participants during the continuous operation investigated herein, it is noted that the highest rating is common to all participants according to RULA and REBA methods. However, the same commonality is not found when analyzing the lowest rating, which varies between participants and design options as shown in Fig. 5. With respect to right and left sides of the body, the total RULA scores indicate that both sides of the body are facing similar ergonomic risks (Fig. 4); while the REBA scores indicate that the right side is most physically demanded; which is aligned with the fact that all participants have the right hand as their dominant hand, and thus, the right side of the body is being most used to perform the tasks. Figure 6 shows a participant performing different tasks in the VR environment; as noted, a broader range of motions is performed by the right side of his body in comparison to his left side.

When analyzing the average RULA rating of each body segment, it is found that the risk on the neck and wrists, both right and left, is lower for all participants in

Fig. 6 Participant (ID 3) performing the different tasks in the VR environment

Design B as observed in Fig. 7; for instance, no body segment obtained a rating of 3 in this design option. Moreover, it is noted that there is no inter-difference between participants in Design B. On the other hand, in Design A, it is found a inter-difference between participants as some participants faced a rating of 3 in their trunk and upper arms. Furthermore, in Design A, all participants obtained a rating of 3 for their necks and wrists. This finding is aligned with the fact that Design B has a lower average RULA risk rating in comparison to Design A. In terms of average REBA rating per body segment, it is noted that the difference between the ratings obtained in each design option is not as significant as those found in the RULA rating. This finding was expected since both design options obtained the same average total REBA rating. Based on the analysis per body segment, it is verified that extra attention should be given to design parameters, such as the angle and the height of the working surface area, that impact on the joint angles of the neck, trunk, and upper arms. This, in turn, impacts on the total risk rating, particularly when using the RULA assessment method which focuses primarily on risks imposed to the upper body.

In addition to the ergonomic risk assessment, the present study also determined the time required to complete the task in both the simulated workstations, Design A and Design B. As summarized in Fig. 8, the time required to finish the task varied from 1:47 to 2:25 ($\tilde{x} = 1{:}50$; $\sigma = 0.01$) minutes in Design A and from 1:40 to 2:04 min ($\tilde{x} = 1{:}43$; $\sigma = 0.01$) in Design B. Therefore, it can be concluded that in Design B the task is performed faster, and participants face lower ergonomic risks. Hence, Design B is selected for further design development. Based on the ergonomic risk assessment performed, it is recommended changes to be made to the angle and height of the work surface of Design B to reduce the risks imposed on workers' trunks. In addition, to address the risks imposed on workers' wrist, it should be investigated

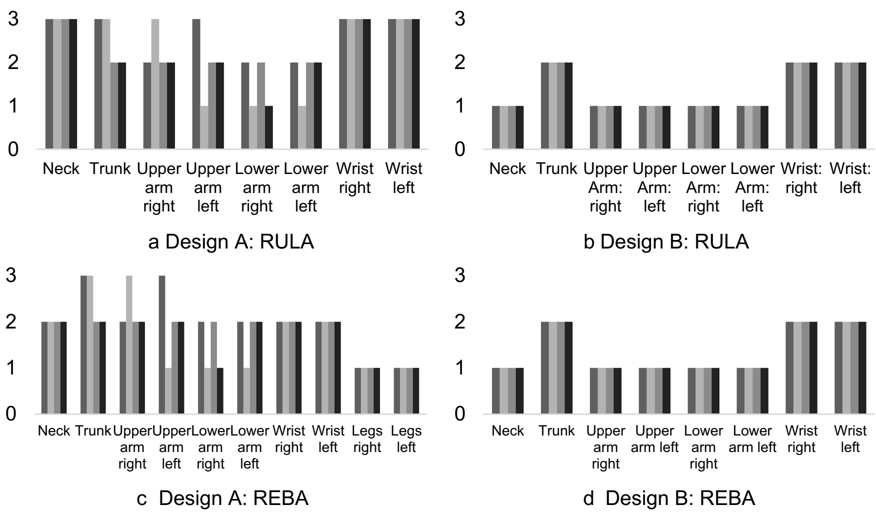


Fig. 7 Risk rating per body segment and participant ($N = 4$) for both design options

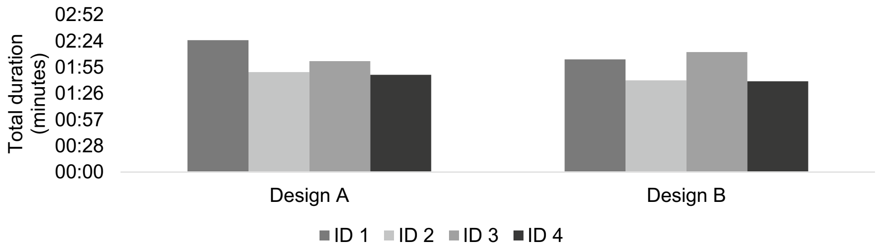


Fig. 8 Time required to finish the task in both design options ($N = 4$)

other types of wireless compact drill driver or other equipment to attach the hardware to the window frame.

5 Conclusion

This study explores the application of a VR-based simulation method that uses body motion data collected by an inertia MOCAP system to conduct ergonomic risk assessment proactively during the design phase of a workstation. Based on the results of the case study, it is determined that both design options require further investigation and changes should be made to both design options to reduce their ergonomic risks. However, between the two options, Design B is chosen for further design development since this option has less ergonomic risks in the higher range in comparison to Design A. In addition, the time required to complete the entire task in Design B is shorter compared to Design A. Taking into consideration the results of the ergonomic risk analysis per body segment, it is recommended that changes should be made to the angle and/or height of the work surface to reduce the risks imposed on workers' necks and trunks while performing the activities at the workstation under study. Once Design B is modified, the method applied in this study can be re-applied to verify the impact of the implemented changes on both REBA and RULA risk ratings. By doing this assessment in a VR environment, speed and flexibility is added to the design development phase, and iterations with physical prototypes are minimized. The directions for future research are to compare the ergonomic risk assessment conducted in this study to those of performed using physical prototypes of both design options in order to verify the accuracy of the analysis performed, include the analysis of joint angles to assess users' body motions, and incorporate other ergonomic decision factors such as reachability and vision analyses to conduct a thoughtful ergonomic risk assessment during the design phases of workstation through a VR-based simulation method. The fact that participants that engaged in the research experiment are not workers that would potentially work in the investigated workstation is a limitation of this study. Furthermore, although participants that engaged in this study represent various percentiles of the population in the United States, this study was run with a small group of participants, which limits the generalization of its results; this limitation will be addressed in the future as this study is developed.

Acknowledgements The authors appreciate the technical writing assistance of Jonathan Tomalty and Kristin Berg. In addition, the authors express their gratitude to Melissa McNeil for assisting in gameplay scripting and designing the 3D scenes used in the VR applications, Anas Itani for providing the design options evaluated in this study, and all volunteers that participated in the experiment. Before recruiting participants to participate in this study, the authors received approval by the University of Alberta's Research Ethics Board, hence, this study's adherence to ethical guidelines related to the observation of humans has been ensured. This work was supported by the Natural Sciences and Engineering Research Council of Canada (NSERC) Discovery Grant [grant number RGPIN-2019-04585] and the University of Alberta.

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Factors Affecting Construction Safety Performance in Saudi Arabia

M. S. Aldossary and A. A. Bubshait

1 Introduction

Construction safety is the focus of local and international authorities since it contributes to providing a healthy work environment, retention of personnel, less project interruption, company reputation and lower insurance costs (Mahdiyar et al. 2018). Unsafe construction practices might lead to project failure through project interruption, decreased productivity, increased construction duration, legal claims and disputes, low staff morale, or other consequences. Incidents due to poor safety performance happen all the time; recorded incidents in Spain alone between 2003 and 2009 totaled 1,163,178 accidents [13]. Additionally, the quality of construction has a positive correlation with safety, as poor safety performance would cause rework, unstable work processes and demolition [21].

Construction safety has a crucial role in Saudi Arabia in supporting the National Industrial Development and Logistics Program (NIDLP), which is intended to transform the Kingdom into a pioneering industrial country [16]. Accordingly, high construction safety performance is required to ensure successful program implementation. Low construction safety performance in Saudi Arabia has resulted in various accidents, such as the Makkah crane catastrophic incident that led to 104 human fatalities and over 400 injuries, huge financial losses for the project, and disputes for all parties involved [1].

Previous studies have demonstrated differences in the relative importance of studied factors. It was observed that differences in importance are highly correlated

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S. Walbridge et al. (eds.), *Proceedings of the Canadian Society of Civil Engineering Annual Conference 2021*, Lecture Notes in Civil Engineering 247,
https://doi.org/10.1007/978-981-19-0968-9_30

with the location of the study. Moreover, studies conducted in Saudi Arabia ranging from 1996 [10] to the more recent study in 2011 by Al Haadir and Panuwatwanich [9] have considered work environment, project factors, practices, construction methods that have been changed due to advancement in construction methods, technologies, standards and enforcement measures. Consequently, knowledge of factors affecting construction safety performance would contribute to mitigating hazards associated with construction accidents.

2 Research Methodology

The research methodology followed to deliver the study objectives consisted of the following phases.

- Performing literature review to gain in-depth understanding of construction safety performance. This was to acquire a well-defined basis for investigating issues related to the study topic. The literature review concluded with a list of 30 factors hindering construction safety performance, which were grouped into seven categories based on their relevance.
- Holding expert interviews to discuss the literature review produced factors and their applicability to construction safety.
- Development of questionnaire survey to assess factors identified in previous steps in terms of frequency of occurrence and importance.
- Conducting pilot testing to validate the developed questionnaire survey prior to its distribution with the advice of professionals. Pilot testing intended to check for clarity and soundness of questions, adding additional factors hindering safety performance and assessing time required to complete the survey.
- Distribution of pilot-tested questionnaire survey to a sample of 76 professionals in the Eastern Province of Saudi Arabia.
- Analyzing data collected through utilizing Frequency Index (FI), Relative Importance Index (RII) and Frequency Adjusted Importance Index (FAII).
- Ranking of factors in accordance with FAII.
- Determining factors ranking level of agreement among respondent classes which were classified into three groups: owners, consultants and contractors.
- Drawing conclusion and recommendations.

3 Identification of Factors Affecting Construction Safety Performance

Based on the literature review performed, expert interviews and pilot study, factors were identified and then grouped into seven main categories that were related to

Project, Personnel, Management, Safety Enforcement Measures, Economy, Environment, and Other Factors. The categorization was in accordance with various levels of construction safety enforcement measures. The categories consist of 30 sub-factors comprised as follows (Table 1):

4 Data Analysis

4.1 Frequency Adjusted Importance Index

The frequency adjusted importance index (FAII) was employed in this study to generate an improved ranking of results through integrating the effects of importance and frequency in Eq. 1 [8]:

$$\text{Frequency Adjusted Importance Index(FAII)} = (\text{RII})\ (\%)^{*}(\text{FI})\ (\%) \quad (1)$$

where

$$(\mathbf{RII})(\%) = \frac{\sum \text{W(importance)}}{\text{A*N}})*100) \quad (2)$$

$$(\mathbf{FI})(\%) = \left(\frac{\sum \text{W(frequency)}}{\text{A*N}}\right)*100) \quad (3)$$

where

W: weight assigned to each factor by participants (1–5), **A:** maximum weight of the study was 5, and **N:** total number of participants.

4.2 Computation of Correlation Coefficient Among Ranks

The correlation coefficients among ranks were computed to evaluate the level of agreement between the classes of respondents, which were owners, consultants, and contractors. The computation was generated through Eq. 4 [7].

$$p = 1 - \frac{6\sum D^2}{n\left(n^2 - 1\right)} \quad (4)$$

where

"p: Coefficient of correlation ranking order", "$\sum D^2$*:* Sum of the squared variances in the ranking of the paired values", *"N:* Number of classes for which the ranking was computed".

Table 1 Identified factors affecting construction safety performance

Category	Factor	References
Project factors	Size of project	[5, 17–18]
	Complexity of project	[5, 18, 24]
	Project working schedule	[8, 15, 17, 22]
	Incompetency of project information	[4, 8, 12, 15, 17, 19, 24]
Personnel factors	Age of personnel	[5, 11–12, 18–19]
	Level of experience	[4–5, 8, 11–12, 18–19, 22, 24]
	Safety behavior	[9, 12, 15, 19, 22–23]
Management factors	Quantity of safety personnel	[1, 4–6, 9, 18, 22–24]
	Management support, involvement and commitment	[2, 4–6, 8–9, 11, 14–15, 18–19, 22, 24]
	Availability and implementation of codes, standards and guidelines	[4, 11, 18, 22, 24]
	Lack of effective communication	[6, 9–12, 14, 18, 22–23]
	Application of safety punishment and reward	[5, 8, 10–11, 18–19]
	Lack of clear responsibility and delegation to staff	[5, 9–11, 18–19, 22]
	Inadequate assignment of teams size	[6, 17–18]
	Authority and competency of supervisor	[6, 18–19, 22]
	Absence of effective accident management	[2, 4–6, 8, 10, 11, 15, 18, 24]
Safety enforcement measures	Lack of safety monitoring and inspections	[2, 4–6, 8, 10–11, 18 24]
	Holding safety meetings	[5–6, 8–11, 15, 18, 22–23]
	Adoption of safety incentives	[2, 6, 8, 11, 15, 19, 23]
	Insufficient safety training and education	[2, 4–6, 8–9, 10–11, 15, 18–19, 22–23]
	Level of safety awareness and knowledge	[4, 6, 8, 10–11, 18, 22–24]
Economic factors	Investment in safety	[4–5, 8, 15, 23, 24]
	Investment in personal protective equipment	[4–5, 8, 10, 15, 24]
	Financial constraints	[4, 15, 18, 24]

(continued)

Table 1 (continued)

Category	Factor	References
Environmental factors	Weather conditions	[4, 8, 12, 20, 22, 24]
	Maintaining safe work environment	[3, 4, 10]
	Implementation of effective housekeeping and maintenance	[8, 10 17–19]
Other factors	Selection and management of contractors and/or sub-contractors	[4, 8, 10, 11, 23]
	Safety equipment/tools procurement and maintenance	[4, 5, 8, 10, 15, 24]

5 Results and Discussion

5.1 Respondents' Characteristics

The respondents had widely distributed professional backgrounds: 20% were Architectural/Building Engineers, 20% responded as Mechanical Engineers, 25% responded as Electrical Engineers, 18% were Civil Engineers and lastly 17% responded that they had other professional backgrounds.

Years of experience indicated that 26% of respondents had 5 to 10 years of professional experience, 61% had five or fewer years of professional experience, 8% had more than 20 years of experience and the remaining 5% had experience ranging between 11 and 20 years.

The participants were classified as: "Owner", "Contractor" or "Consultant". The results showed that 43% of respondents were categorized as owners, 32% of respondents were working in the contracting sector, and the remaining 32% were in consultancy.

5.2 Factor Assessment

The results of respondent assessment of factors affecting construction safety performance in terms of frequency of occurrence (FI), importance (RII) and frequency adjusted importance (FAII) are presented in Table 2. The results presented are for each class identified, i.e., owners, contractors, and consultants, including an overall assessment of all classes involved.

Table 2 Factor assessment

Category	Factors	Owners				Contractors				Consultants				Overall	
		FI	RII	FAII	Rank	FI	RII	FAII	Rank	FI	RII	FAII	Rank	FAII	Rank
Project factors	Size of project	70	80	56	5	66.7	66.7	49.4	8	68.4	81.1	55.5	3	53.9	4
	Complexity of project	74.7	78.8	58.9	1	64.2	64.2	46.5	15	59	74.7	44.1	18	50.9	9
	Project working schedule	69.4	77.1	53.5	9	70	70	51.9	7	66.3	69.5	46.1	13	51.2	8
Personnel factors	Incompetency of project information	58.2	67.1	39.1	20	55	55	35.8	27	59	59	34.8	26	36.8	27
	Age of personnel	53.5	60.6	32.4	28	65.8	65.8	46.6	14	51.6	62.1	32	28	36.4	28
	Level of experience	61.2	68.8	42.1	17	73.3	73.3	56.8	4	65.3	69.5	45.3	17	47.2	13
	Safety behavior	71.2	78.8	56.1	4	78.3	78.3	62.7	1	71.6	75.8	54.3	4	58	2
	Care for safety	71.8	78.8	56.6	3	75.8	75.8	61.9	2	83.2	79	65.7	1	60.0	1
Management factors	Quantity of safety personnel	64.1	70	44.9	16	65	65	45.5	17	62.1	63.2	39.2	22	43.1	15
	Management support, involvement and commitment	68.8	78.2	53.8	8	65	65	47.1	12	64.2	72.6	46.6	11	49.4	10
	Availability and implementation of codes, standards and guidelines	72.9	75.9	55.4	6	72.5	72.5	53.2	6	69.5	71.6	49.7	8	52.9	5

(continued)

Table 2 (continued)

Category	Factors	Owners				Contractors				Consultants				Overall	
		FI	RII	FAII	Rank	FI	RII	FAII	Rank	FI	RII	FAII	Rank	FAII	Rank
	Lack of effective communication	57.7	61.8	35.6	25	57.5	57.5	33.5	29	66.3	70.5	46.8	9	37.6	23
	Application of safety punishment and reward	58.8	65.9	38.8	21	60	60	41	22	64.2	67.4	43.3	20	41.1	20
	Lack of clear responsibility and delegation to staff	52.9	60	31.8	29	60	60	36	25	69.5	74.7	51.9	6	37.2	25
	Inadequate assignment of teams size	60.6	60	36.4	24	61.7	61.7	37	24	60	56.8	34.1	27	35.7	29
	Authority and competency of supervisor	67.7	70	47.4	14	65.8	65.8	43.9	19	63.2	73.7	46.5	12	46.1	14
	Absence of effective accident management	48.2	62.4	30.1	30	55	55	32.1	30	60	63.2	37.9	23	32.3	30
Safety enforcement measures	Lack of safety monitoring and inspections	53.5	62.9	33.7	27	55.8	55.8	35.4	28	65.3	71.6	46.7	10	37.0	26
	Holding safety meetings	60	68.8	41.3	18	56.7	56.7	39.7	23	60	61.1	36.6	24	39.4	21

(continued)

Table 2 (continued)

Category	Factors	Owners				Contractors				Consultants				Overall	
		FI	RII	FAII	Rank	FI	RII	FAII	Rank	FI	RII	FAII	Rank	FAII	Rank
	Adoption of safety incentives	58.2	63.5	37	23	63.3	63.3	43.3	20	59	60	35.4	25	38.9	22
	Insufficient safety training and education	52.9	64.1	33.9	26	68.3	68.3	48.4	10	49.5	57.9	28.6	30	37.4	24
	Level of safety awareness and knowledge	66.5	74.1	49.3	12	68.3	68.3	49	9	69.5	72.6	50.5	7	49.3	11
	Investment in safety	67.1	71.8	48.1	13	57.5	57.5	35.9	26	61.1	67.4	41.1	21	42.2	17
Economic factors	Investment in personal protective equipment	74.1	77.7	57.6	2	64.2	64.2	47.1	13	72.6	71.6	52	5	52.3	6
	Financial constraints	58.2	64.7	37.7	22	65	65	44.4	18	67.4	67.4	45.4	15	41.4	19
	Weather conditions	56.5	69.4	39.2	19	60.8	60.8	43.1	21	63.2	72.6	45.9	14	42.3	16
Environmental factors	Maintaining safe work environment	69.4	77.7	53.9	7	72.5	72.5	56.8	5	74.7	76.8	57.4	2	55.6	3

(continued)

Table 2 (continued)

Category	Factors	Owners				Contractors				Consultants				Overall	
		FI	RII	FAII	Rank	FI	RII	FAII	Rank	FI	RII	FAII	Rank	FAII	Rank
	Implementation of effective housekeeping and maintenance	65.9	75.9	50	10	65	65	47.7	11	67.4	67.4	45.4	16	47.8	12
Other factors	Selection and management of contractors and/or sub-contractors	61.2	75.9	46.4	15	65.8	65.8	46.1	16	52.6	56.8	29.9	29	42.1	18
	Safety equipment/tools procurement and maintenance	65.3	76.5	49.9	11	75	75	60	3	61.1	71.6	43.7	19	51.4	7

Table 2 demonstrates detailed assessment of the factors, as perceived by professional practitioners grouped into owners, contractors, and consultants. Overall assessment of the factors indicated that the factors with the highest impact were "care for safety", "safety behavior", "maintaining safe work environment", "size of project" and "availability and implementation of codes, standards and guidelines". Factor ranking was in accordance with the frequency adjusted importance index (FAII).

5.3 *Rank Importance Correlation*

The importance correlation among ranks was computed to measure the level of agreement for each class involved. The results concluded with a correlation coefficient of 0.69 among "Owners and Contractors", 0.54 among "Owners and Consultants", and 0.40 among "Contractors and Consultants". As all correlation coefficient values among ranks were positive, this implies that all the stakeholders involved in the questionnaire survey are in agreement on the significance and frequency of the factors.

6 Conclusion and Recommendations

The investigation of factors affecting construction safety performance was based on a literature review, experts' interviews, and pilot study, from which factors were identified and then grouped into seven major categories, namely, "Project Factors", "Personnel Factors", "Management Factors", "Safety Enforcement Measures", "Economic Factors", "Environment Factors", and "Other Factors". The categories were comprised of 30 sub-factors. A questionnaire survey was distributed to 76 professionals, each of whom were classified as "Owner", "Consultant" or "Contractor" based on their work function. The "care for safety" factor was rated highest among all the factors, with almost 60% on the frequency adjusted importance index (FAII), and "safety behavior" rated second with 59% on the FAII.

The study concludes with the following recommendations:

Safety professionals must be self-motivated in their safety practices as the "care for safety" factor was highest ranked among the factors identified.

The list of factors identified provides a clear view of the main causes of deficiencies in safety performance, which safety professionals may utilize in improving safety performance levels through eradicating or mitigating risk factors.

A list of factors affecting construction safety performance in Saudi Arabia has the potential to help the government and engineering council in developing safety improvement plans and measures.

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Exploring Potential Building Materials for Planet Mars

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1 Introduction

We, the human species, are pioneers and explorers who had first conquered land then seas and skies. The next logical step in our quest for expansion is to look farther away than our own planet and search the cosmos for possible homes to house us in case we need shelter from extraordinary events that might ensue us. Economic interest also arises when talk of interplanetary travel is the subject at hand because planets have a priceless wide array of untouched resources (Orwig, para 3). Numerous hazards, however, exist on the red planet that must be thought about before this leap is taken. Galactic cosmic rays, lack of water in liquid form, toxic soil and ice, and cold temperatures are some of these challenges.

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S. Walbridge et al. (eds.), *Proceedings of the Canadian Society of Civil Engineering Annual Conference 2021*, Lecture Notes in Civil Engineering 247,
https://doi.org/10.1007/978-981-19-0968-9_31

National agencies and private enterprises have, both, shown great interest in colonizing planet Mars. NASA, SpaceX, and Blue Origin are some of these agencies working on establishing colonies on Mars. SpaceX has a plan to establish a colony of 1 million people living on mars in the next 50–100 years. The first humans to reach the red planet by SpaceX's timeframe will do so in 2024 (Wall, para 5). NASA has a more conservative time frame of 2030. Establishing colonies on Mars will require a great feat, to say the least, of aeronautical engineering but also innovative solutions of constructing shelter using methods and materials that are both practical and feasible. Materials have to offer the protection needed from the aforementioned hazards while maintaining practicality of execution.

The objective of this report is, therefore, to explore the building materials available on planet Mars and studying ways of utilizing them in shelters along with feasibility analyses to come up with a complete proposal of shelter that can be built on the red planet for use as shelter in the near future. The primary building material on Earth is concrete which makes use of aggregate that is part of our planet itself. The case will be similar on planet Mars but the absence of water makes it impractical to use cement as a binding agent. Mars is rich in Sulphur, however, which when melted is a binding agent in of itself. The melting point of Sulphur is 115 degrees Celsius which is reasonable to reach and maintain. Martian concrete made up of simulated Martian regolith and molten Sulphur was mixed in ratios of 2:3, 3:2, 1:1 aggregate to Sulphur ratios and tested for compression and flexure by ASTM standards. Alternative materials are also discussed and assessed based on practicality and feasibility.

2 Literature Review

According to journals and findings, when comparing between sulfur concrete and Martian concrete through various tests such as sieve analysis, microscope studies, and X-ray photoelectron spectroscopy analysis, it was evident that Martian concrete has a higher compressive strength of above 50 MPa and has also a higher strength in other properties due to its particle size distribution and formation of sulfates and polysulfides. Furthermore, several sulfate mixes were provided by several journals incorporating a Kuwaiti journal stating that Kuwait is one of the largest producers of sulfur producing 0.9 million tons/year which can aid in simulants.

Research also conveyed that Martian simulant can be formed from volcanic glass with a mix of basalt. A simulant with the same chemical, mineralogical, and physical properties as Martian regolith was made from a combination of volcanic glass collected from two banks in New Zealand in addition to blending of basalts.

Other findings also proposed several concepts which incorporate:

- Production of steel Mars

  Mars is an ore-grade hematite. Thus, it has large portions of metallic iron available so without the energy-intensive process of reduction, the production of steel on Mars can be much easier and less energy intensive than on Earth.

- Design concepts:

  Stationary and mobile- built on-surface, or within lava tubes that can withstand hard and unique Martian conditions.

According to several findings, there are materials available on Mars that could be used for construction. These materials could be categorized into metals and regolith. Regarding the metallic materials, metals such as magnesium, aluminum, iron and titanium could be mined on planet Mars, but they require a lot of energy to melt and mold, as well as being very expensive to process. Regolith, on the other hand, is abundant on Mars and cheaper. Cast regolith, Martian concrete and duricrete are potential by-products of the regolith found on the red planet. Cast regolith consists of melting Martian soil and shaping it into the structural components needed for construction, such as beams or columns. However, Martian concrete is very similar to sulfur concrete and requires little energy for production. Martian concrete is a concrete mix that consists of molten sulfur and Martian soil with a gradation that is lower than 1 mm. The binding reagent in the concrete mix is the molten sulfur. Through research, Martian concrete is believed to have a compressive strength of 50 MPa, making it suitable for large structures due to its high compressive strength. Whereas duricrete is the mixture of regolith and a relative weight of 3% water, that is hydraulically pressed and shaped into bricks. Duricrete is a building material on Mars that is comparable to masonry bricks on Earth. They could be used for inner walls of a structure or any structural component that does not experience high loads due to its low compressive strength of 5 MPa.

3 Objective and Scope

In this research, the main objective was to investigate and select an adequate building material to be potentially used for building on planet Mars in a feasible manner. This objective was obtained through evaluating several building materials on Earth that can be suitable for planet Mars which includes Martian Concrete, Duricrete and Aluminum as well as exploring construction methods and the feasibility of Martian building in light of various parameters such as weather and gravity, etc.…

4 Experimental Work

4.1 Material Properties

1. Martian Soil will be simulated with Basalt as it has been proven to have somewhat similar chemical and elemental composition as the Basalt.
2. Pure Sulfur is also used in the mix.

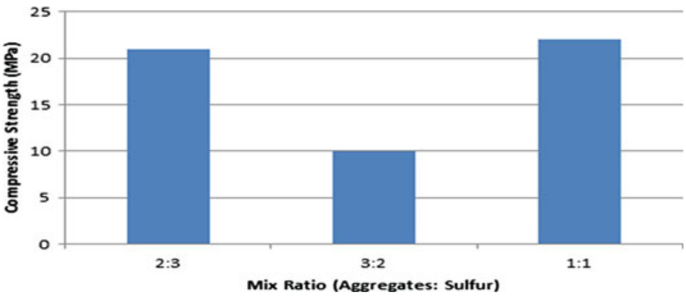

Fig. 1 Mix ratios versus compressive strengths

Martian Concrete:

The highest compressive strength was achieved by the 1:1 mix resulting in 22 MPa. Although the cube of 1:1 mix was poured incorrectly and the other two mixes were poured correctly, the 1:1 mix was still the highest compressive strength. Before applying the mix, molds, spoons and aggregates should be heated with the same applied temperature to the molten sulfur. Moreover, molds should be greased as well as the mix should be poured continuously to avoid voids occurrence in the cube (Fig. 1).

Basalt EDX:

5 Results and Analysis

5.1 Construction Methods

Construction on Mars and even other remote places here on Earth has always been a challenge. The conventional method of construction for concrete requires the use of heavy machinery to transport the required equipment first and then use conventional formwork and concreting techniques. This approach will not be ideal in establishing humans' first Martian colony because it will be extremely expensive and hazardous to human labor. The lack of shelter on Mars entices the finding of innovative construction methods that can be deployed before humans reach their destination.

5.1.1 3D Printing and Contour Crafting

3D printing used in construction applications is known by contour crafting. Contour crafting has real potential for use on Mars and even remote places here on Earth because it does not require the use of neither formwork nor the ordinarily used quantity of labor in construction. This approach is mostly autonomous requiring only the use of pre-programmed printers that move in 3D space to print structures in layers. The currently functional uses of this process, however, requires the erection of large frames on which the printing nozzles will move. In our case, the transportation of these frames and their assembly will be very difficult due to their size and level of intricacy they have to be designed on. The use of these frames will also mean that once one structure is finalized, the frames used to construct it will not be able to work on another because they need to be reassembled and moved.

To tackle this issue, the NASA Innovative Advanced Concepts (NIAC) program has proposed a concept to adopt contour crafting using existing robotics and material processing technology. This idea proposes the use of rovers that are equipped with 3D printers and material processing parts. The method such robots will function will be by shoveling sieved regolith and using it by employing a nozzle system that would hot mix it with Sulphur and print it in pre-programmed details to construct the required structure. The flowability and workability of the concrete mix will definitely play a big role here because it has to flow seamlessly through the nozzle. Our concrete mix of maximum aggregate size of 1 mm will be very handy here because the small aggregate size is suitable for this application.

5.1.2 Proposed Construction Method

NASA has hosted a competition which had a goal of designing 3D printed habitats for planet Mars. The use of materials in the competition was not restricted to Martian concrete or regolith. The competition's winner, SEArch/Clouds Architecture Office, proposed to build housing units using 3D printed ice because it already exists in the Martian crust and also enclosing the house in an ultra-high-molecular-weight-polyethylene (UHMWPE) wrapping layer. The UHMWPE layer will provide protection against Mars's dust storms and weather irregularities while the ice will provide adequate protection against radiation (Garner 2017). Another team, A.R.C.H, proposed the use of Martian concrete, which we have tested to build a "Donut House" which as the name entails is shaped like a hollow circle which is divided into sections. The sections can be closed off in case of accidents and put out of commission while still granting access to the rest of the structure using its circular shape.

Our team proposes an integrated habitat model Integrating both SEArch/Clouds Architecture office's and A.R.C.H's solutions. Our structure concept is of a "Donut House' enveloped by a UHMWPE layer and an ice layer to provide maximum protection and also to utilize Martian concrete which we view as the most suitable building material for planet Mars. The sequential conceptual method of construction we propose is as follows:

1. Payload arrives and air from landing thrusters clears site.
2. WaSiBo, the ICE home's sintering concept robot, is deployed and collects regolith and laser sinters it into a foundation.
3. UHMWPE membrane inflates and forms the outer boundary of structure.

4. iBo, the 3D printing rover, is released and specialized units harvest ice for Insulation and regolith and Sulphur for the main shell.
5. iBo prints the insulating ice layer.
6. Specialized iBo units 3D print main shell and interior walls.
7. Crew arrives and moves in.

5.2 Feasibility

While this work is mainly focused on the construction aspects, other vital aspects need to be closely looked upon because they are quite vital for the success of the project. Feasibility is definitely an aspect that should be discussed as building on mars is no simple matter and requires responding to a variety of questions that will eventually come up before tackling the question of building on Mars. While this is a farfetched idea, it will indefinitely come into the picture in the near future. It must be noted; however, that technology continuously advances and prices change as time goes on so the prices listed here are tentative and only serve as a benchmark for further investigations and inquiry. The questions that need to be answered are divided into 3 categories.

- Launching into space
- Establishing a human colony on Mars
- Surviving on Mars

Launching into Space:

It is without a doubt that humanity cannot bring with it building materials like cement or steel to Mars due to the fact that these items will not only take space and weight on the space shuttle that can be better utilized for other essentials, but also inflate the costs of going to Mars to unfeasible amounts. Rockets have weight limits, for example, Falcon 9, from Space X, costs $62 Million USD and can only carry 4 tons while the Falcon Heavy costs $90 Million USD and can carry 16.8 tons which is a significant improvement; however, assuming 12 people going to Mars would need food and water for 2 years stands around 25 tons of food and water (SpaceX)(Brain). Neither the Falcon Heavy nor the Falcon 9 have that sort of capacity; however, the Starship does. The Starship can handle 100 + tons at a cost of $10 Billion USD, which means $100 Million USD per ton including development and equipment costs (Davis, 3). It is important to note that without development costs, the starship launch cost is anticipated to be $2 Million USD (SpaceX).

Establishing a Human Colony on Mars:

When it comes to establishing a human colony on Mars, the survivability of the humans relies on how well the infrastructure can protect them from the harsh weather conditions, and radiation conditions on Mars. Humanity cannot bring building materials with it from Earth that will protect it from these harsh conditions, but it can bring with it equipment which can help it build a permanent home on Mars from the materials which exist on Mars, so humanity is only limited by how much equipment it is capable of transporting from Earth. The building materials chosen: 1. Duricrete 2. Martian Concrete 3. Aluminum Alloys (5083 & 6061) are quite capable of protecting the humans from the harsh conditions on Mars. The equipment availability for making these building materials will be discussed later on in this paper.

Surviving on Mars:

Moving on to surviving on Mars, humanity will require food, energy, water, and oxygen. Food can be produced using bioengineered plants & Aquaponic controlled environments (Llorente). Energy can be obtained from small scale nuclear fuel cores from NuScale which costs around $250 Million USD or from Solar Energy or from CO2 combined with Hydrogen to produce Methane and Water (Black)(Dunbar). Water can be drilled, melted, and filtered for any use while oxygen can be produced through the electrolysis of water (Dunbar). The Zero Liquid Discharge treatment system for water costs $3 Million USD, but can produce 30 gallons per minute (SAMCO).

Feasibility of Chosen Building Materials:

When it comes to transporting the equipment needed to build on Mars. Duricrete needs a hydraulic press to make the bricks and this can be easily automated to make a quick and fast building material with just feeding in the soil, water, and energy. Instron 5582 compactor costs $36,000 USD along with the automatic sieving machine and oven both $5,000 USD each. The prices of all these machines are available on Ebay. With automation, this process will be effortless. UR16, $45,000 USD, biggest of all universal robots helper hands can help significantly (Universal Robots). There are also bigger industrial robots that range from $100 to $150 thousand USD for heavier, more industrial work (RobotWorx). For Martian Concrete, Robotic Arm 3D printers like the ones from MARSHA and Stratasys reduces the labor of building by 90%, and is extremely feasible in construction on Mars (AI Spacefactory). The costs of such a machine being built to work on Mars are unknown but the project has proven its success on Earth (AI Spacefactory). Without the 3D printing arm, what is needed is a kiln, an automatic sieving machine, and regular 3D printer to form the construction molds needed to pour into. Again this can be easily automated using the U16 robot, that weighs 36 kg and can carry 16 kg, or a heavier industrial robot (Universal Robots). Aluminum; however, is feasible but after a colony has already been established with multiple shuttles carrying various equipment have been delivered due to the lengthy process of making Aluminum from bauxite. Aluminum made from bauxite requires 2 equipment and energy intensive processes, the Bayer process and the Hall Heroult process, both of which are unfeasible to transport to Mars for now (Carlson) (Table 2).

The recommendations of each aspect discussed in this section is in Table 1 along with their cost. Such cost accounts for a minimum of 2 years' worth of nuclear energy as one core can produce 50 megawatts and the fuel can last for 2 years, and since this fuel cannot be renewed on Mars then it is needed to send to Mars more nuclear fuel as time passes on (Cunningham)(Modern Power Systems). Solar Panels can also be used; however, they are deemed unreliable due to the dust storms and dust devils that regularly occur on Mars and can block sunlight planet wide for months at a time

Table 1 EDX results of used basalt

Element		(keV)	Mass %	Counts	Sigma	Atom %	Compound	Mass %	Cation	K
C K		0.277	1.47	100.0	0.10	2.97				3.1932
O K		0.525	30.13	5307.56	0.48	45.67				1.2344
Na K		1.041	2.15	492.90	0.16	2.27				0.9497
Mg K		1.253	2.48	581.55	0.18	2.47				0.9256
Al K		1.486	9.71	2165.39	0.35	8.73				0.9754
Si K		1.739	29.28	6367.20	0.61	25.28				1.0000
Ca K	(Ref.)	3.690	10.77	1387.28	0.46	6.52				1.6876
Fe K		6.398	14.02	803.73	0.75	6.09				3.7930
Total			100.0			100.0				

Thin Film Standardless. Standardless Quantitative Analysis.
Fitting Coefficient: 0.0696.

(Black). Enough time for the astronauts to lose heat energy and suffer in the cold winters of Mars. The recommendation for food and oxygen are unknown due to the fact that biologically engineered plants are still being tested, and a question of size relates to the price of aquaponic controlled environments; however, these systems are not costly and are thus negligible in the grand scheme of prices. The total price tag is 10,253,806,000 USD but to account for any changes or special modifications for the equipment for usage in space then it is safe to round up to 10.260 Billion USD. It is important to note that these costs are tentative and can be reduced or increased and justified with the advancement of technology, especially rocket science, as well as scheduled human missions to Mars; furthermore, this total cost accounts for the first mission to Mars as missions after the first mission will not require as many equipment, development costs, and will most likely reuse or recycle much of the equipment already brought on by the first mission.

5.3 Factors Affecting Living on Mars

Availability:

As previously mentioned, Martian concrete and Duricrete are both adequate building materials that could be potentially used for building on planet Mars in a feasible manner. Both Martian concrete and Duricrete are excessively available. Martian concrete is a mix of Martian soil and sulfur which is abundant on Mars. Duricrete consists of Martian soil and three percent of water which is also abundant on Mars. Waste water from humans can be used in forming Duricrete. In addition, there are tons of water in the polar ice caps. It is 1000 km across and contains

Table 2 Total cost of sending 12 astronauts to mars

Item	Estimated price
Starship	$10 Billion USD
NuScale (Nuclear reactor)	$250 Million USD
Food and oxygen	Negligible
Instron 5582 compactor	$36,000 USD
Zero liquid discharge treatment system (30 GPM)	$3 Million USD
Industrial robots (Price per 1 Robot)	$150,000 USD (Multiply by 2)
3D Printing robotic arms	Unknown price tag (Assume $300,000 × 2)
Automatic sieving machine + ovens (2 of Each)	$20,000 USD
Total price tag	$10,260,000,000 USD (Rounded up)

approximately 1.6 million cubic km of ice (IAA-CSIC,11). Melting the ice can be done through two simple methods:

1. First Method:
   a. Compress carbon dioxide gas, which is the most abundant element in the Martian atmosphere.
   b. Pass the gas over Martian regolith
   c. Carbon dioxide will then dissolve some of the water confined in the soil
   d. As the gas expands, it releases clean water that can be collected and stored.
2. Second Method:
   a. Ion Exchange:
      i. Collect saturated soil
      ii. Heat it to 500 °C
      iii. Collect the steam and condense it into pure desalinated water

Perchlorate:

Another factor affecting living on mars is perchlorate. Since Martian concrete only includes 0.5–1% perchlorate, ion exchange will be used for water treatment. On the other side, since duricrete has a high percentage of perchlorate due to its existence of water, reverse osmosis will be used. It is a common method used on Earth which involves a thin plastic membrane which has holes in it as shown in the figure below. This thin plastic membrane is small enough to let the unnecessary out but large enough to let water through [1] (Fig. 2)

The figure below shows several perchlorate treatments and their costs. Since perchlorate on Mars exists in low concentrations, ion exchange and reverse osmosis are the two applicable treatments to be applied. Biologics were eliminated because it

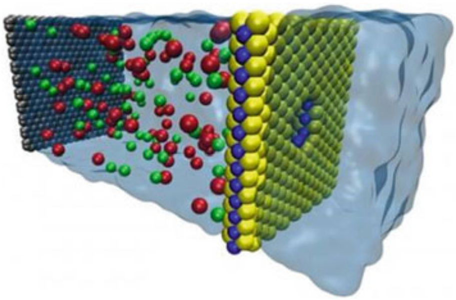

Fig. 2 Reverse osmosis http://marsforthemany.com/project/living-on-mars/making-clean-water-on-mars/

would require utilizing bacteria to get rid of the perchlorates. However, introducing bacteria to Mars does not abide by the vision of keeping Mars as pristine as possible. The costs of both treatments, whether ion exchange or reverse osmosis, may not be cheap on Earth but are actually affordable compared to the budget devoted for building on planet mars. Of course, these treatments are done on Earth and not exactly in the same Martian conditions but they seem to be promising. Besides this, perchlorate can be reusable since igniting it can act as a rocket fuel which can produce another source of energy and allow us to be self-sufficient on mars (Fig. 3).

Psychology and Health Conditions:

There are many psychological and health challenges the crew destined for Mars that must be overcome:

Radiation:

The donut ice house is designed to withstand intense radiation and massive daily temperature changes, while providing a pressurized environment inside for humans to inhabit over a prolonged period of time. Radiation on Mars is 5000 times more than on Earth, however, the Donut Ice House will have a thick outer layer of ice which would protect the interior from radiation. Most materials that block radiation are opaque which makes any home dark, impacting one's psychology. However, with a thick outer layer of ice in the applicable structure, there will be no need for opaque.

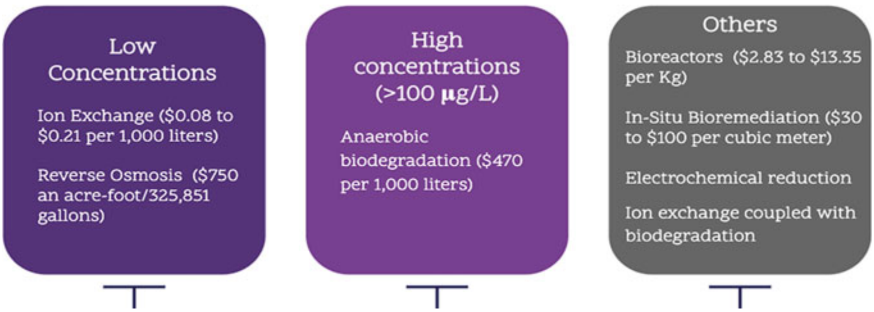

Fig. 3 Perchlorate treatments

Gravity:

Training programs to adapt and enhance the ability to detect relevant sensory input are being investigated by NASA to mitigate balance control issues.

Isolation and Confinement:

The use of underground structures will be avoided. Furthermore, the membrane around the donut ice house will be transparent to allow light in the building and thus prevent the feeling of isolation and confinement. In addition, methods for monitoring behavioral health and adapting several tools and technologies are evolving to detect and treat early risk factors. Furthermore, research is being conducted in:

- Workload and performance
- Light therapy for circadian alignment
- Phase shifting and alertness.

Distance:

Planning in advance and self-sufficiency would be critical keys to a successful Martian Mission.

6 Limitations and Obstacles

Limitations:

Several limitations arose during the experimental works conducted throughout the research. Firstly, none of the literature reviews stated how they had conducted their experiments. Therefore, it was necessary to conduct several trials to perfect the mixing method between the molten sulfur and the aggregates to ensure that the molten sulfur does not harden before the mixing is completed and ensure a continuous pour of the concrete to avoid any voids in the samples. Moreover, the fumes that were present as a result of melting the sulfur were hazardous. This limited our working hours in the lab because we had to conduct our experiments during times where the lab was empty because we did not have enough masks to give out to other students or professors that could have been present in the lab at the same time. Consequently, we were confined by the working hours of the lab. Finally, the process of crushing and sieving the aggregates to get the gradations we needed was time-consuming because we used the L.A Abrasion testing machine to crush the aggregates; so we were limited to the amount of aggregates that could be crushed in one cycle.

Obstacles:

Due to the complexity of the topic, there is a scarcity in the data information available for building on Mars because the issue deals with much more than the conventional building materials and methods that are used on Earth. Furthermore, there was the limitation and difficulty of obtaining adequate materials for testing that would possess similar chemical and physical compositions of Martian soil. In addition to obtaining adequate materials, simulating all the Martian conditions was not possible as we did not have all the experimental machines we needed; therefore, we had to narrow down the conditions that were to be simulated. Finally, due to the restricted time, a huge obstacle that we have faced was to narrow down and conduct a rational comparison between the materials to analyze their feasibility and select the material accordingly.

7 Conclusion

Basalt has similar chemical composition to Martian Soil. Secondly, the 1:1 sulfur to basalt mix resulted in the highest compressive strength. Moreover, treatment of perchlorate in Martian soil and water is promising. Also, of the materials investigated, Martian concrete and Duricrete are two feasible building materials for use on Mars as they also exist in abundance. Furthermore, a specially modified 3-D printing is a promising method for construction on extraterrestrial bodies. Last but not least, the cost estimate for building a colony on Mars is $120 billion, such cost can be reduced and justified with the advancement of technology as well as scheduled human missions to Mars. Martian concrete is a selected option amongst various options as it appeared to be one of the most feasible materials to be used potentially as a building material on planet Mars, moreover, duricrete can be considered as a second option as a building material. Due to duricrete's lower strength than Martian concrete, as well as its ease in the construction process, it is considered to be a second option as a building material for other purposes such as interior walls. Aluminum requires a huge source of energy in order to be produced and constructed and its process is not easy, which leaves us with Martian concrete as the selected first option.

8 Recommendations

The experimental work suggested in this study needs to be expanded upon using other materials, dosages and techniques. Also, many of the tests tackled in this study need to be repeated under conditions as close as possible similar to the ones existing on planet Mars. In addition, prepared basalt should be available to ease the gradation process. And most importantly, in order to achieve fair comparison and high compressive strength for different mixes, the following precautions should be taken into consideration, continuous method of pouring the mix, prior heating of the equipment and the materials and greasing the molds. Also, tackle future work with an integrated team, comprising engineers, scientists and other human resources to consider all other factors including psychological, health, long term exposure and living conditions on planet Mars. Not only to continuously update the tentative cost as technology advances but also to design and build prototypes of the 3D printing robots and test their functionality in Martian conditions. Furthermore, carry out a thorough structural analysis contour crafting with Martian concrete in order to obtain an adequate design for building on Mars. finally, perform further testing while taking other vital parameters such as radiation, temperature variations, change in gravity, etc.…

Acknowledgements This work was recommended and counseled by Dr. Mohamed Nagib Abou-Zeid.

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Sensing and Data Collection Methods for Occupant-Centric Building Control: A Critical Review of State of the Art

H. Karimian, M. Ouf, N. Cotrufo, and J. Venne

1 Introduction

Occupants spend approximately 90% of their time in buildings, living and working [4]. Therefore, understanding the dynamic and diverse occupant comfort needs as well as occupant interactions with building systems is crucial. Building design and operations must meet energy performance goals while providing healthy and productive living and working environments. At the same time, occupants influence building performance, while buildings influence their comfort levels. Occupant actions such as adjusting a thermostat, switching lights on/off, using appliances, opening/closing windows, pulling window blinds up/down, and moving between spaces can significantly impact both energy use and occupant comfort [26].

Over the past years, there has been widespread adoption of various approaches to increase energy efficiency and occupants' comfort in buildings. Among those, due to the improvements in sensing infrastructure and data mining, Occupant-Centric building Control (OCC) has been introduced. OCC is a novel approach for indoor climate control which aims to deliver building services only when and where they are needed, in the amount that they are needed. Many researchers suggested that OCC can achieve considerable energy savings up to 60% [40]. However, obtaining occupants' data and preferences is typically challenging because of their dynamic and unpredicted behaviors. As a result, inaccurate assumptions are usually being used in building operations, which often leads to wasteful energy use (e.g., heating empty spaces, or providing ventilation rates that exceed indoor air quality requirements) [37]

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S. Walbridge et al. (eds.), *Proceedings of the Canadian Society of Civil Engineering Annual Conference 2021*, Lecture Notes in Civil Engineering 247,
https://doi.org/10.1007/978-981-19-0968-9_32

or may trigger occupant discomfort. Most data collection techniques, especially for human-building interactions can only be utilized after occupants have entered the buildings (post-occupancy phase). Furthermore, adequate sampling of occupants' behavioral data requires extensive time and resources. However, other approaches relying on building simulations have been investigated to address this issue [38]. In such case, samples size, location, and the duration of the sampling process can be easily varied to represent a wider range of scenarios.

Figure 1 demonstrates an overview of the OCC approach, in which occupant information (e.g., presence, count, and interactions with building systems) and indoor/outdoor environmental parameters (e.g., temperature, humidity, and CO2 concentration) are detected and transferred as a feedback signal to the control system. Control algorithms find optimal setpoints for zone parameters (e.g., temperature, illuminance, ventilation), accounting for occupant comfort models and feedback, then implementing the chosen control action [1]. To this end, the aim of this paper is to provide an overview of the approaches used in sensing and acquisition of occupants' behavior and preferences to develop OCC for buildings with the dual goal of reducing energy consumption in buildings while improving occupant comfort. In the following sections, different data collection requirements and methods will be compared to understand the research gaps, and to provide a future research roadmap.

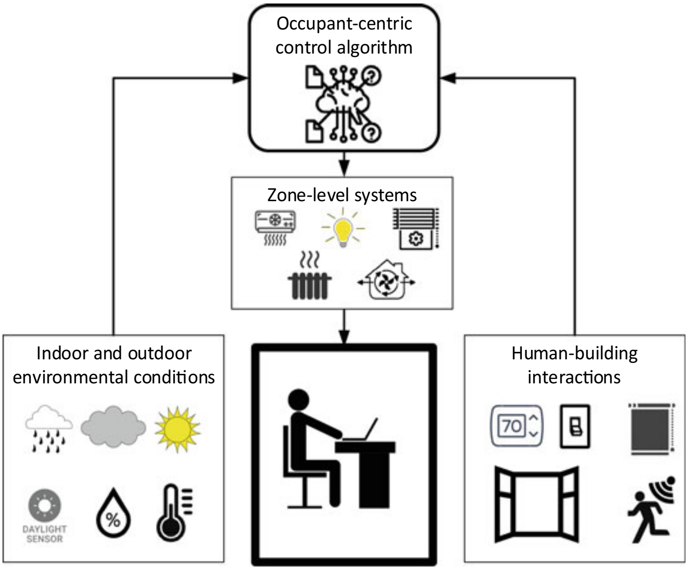

Fig. 1 Overview of OCC approach

2 Review Method

The publication list was selected by searching with the relevant keywords (e.g., Occupant-centric control, Occupants' data, Occupants' sensing, Occupants' behavior, and Occupants' preferences) in both general data bases (e.g., Google Scholars, ScienceDirect), and topic-specific journals (e.g., Building Performance Simulation, Energy and Building, Building and Environment). Papers that did not fit our specific purpose (i.e., occupants' data collection and sensing approaches used in OCC research) were excluded, which resulted in a total of 87 publications. Firstly, the bibliographical information of the papers was analyzed, and then the data acquisition requirements and techniques/tools were investigated in more depth.

The gathered publications were analyzed with regards to their year of publication, building type, and monitored duration. As shown in Table 1, approximately 70% of the papers were published in the last four years (2016-present), which highlights the growing interest in this topic. A breakdown of the identified publications by building type is then provided. In more than half of previous studies, occupants' data were collected in office buildings. Academic buildings were the second most frequent. In Table 1, a breakdown of the monitored duration in identified OCC studies is also illustrated. The monitoring duration of OCC studies was limited to 2 months in more than 70% of the identified studies. Furthermore, the geographical distribution of identified OCC studies suggests the majority were in the United States and Canada.

Another aspect was analyzing the occurrence of each keyword in total, which were done with the aid of a text-mining tool. Paper titles and keywords were text-mined to investigate the total number of occurrences of each keyword. Figure 2 depicts the top keywords with the highest number of occurrences. As it is expected when considering publications on OCC topic, the keywords "Occupant", "Data" and "Collection" had the maximum numbers of occurrence, and are presented in light yellow. Subsequently, high occurrences of several words such as "adaptive", "intelligent", "learning", "algorithm", and "virtual" clearly suggests that the direction of the academic research in OCC would be mostly focused on automation and digitalization of data collection approaches. Other keywords with high probability of occurrences can be observed below as well with the color strength representing their frequency

Table 1 Bibliographical information of the analyzed papers

Year of publication	Percentage of papers (%)	Building type	Percentage of papers (%)	Monitored duration	Percentage of papers (%)
2016–2020	70.3	Office	55.6	Less than a week	20.2
2012–2016	18.85	Academic	16.7	1 month	9.8
2008–2012	6.75	Residential	11.1	2 months	41
Before 2008	4.1	Commercial/other	16.6	More than 2 months	29

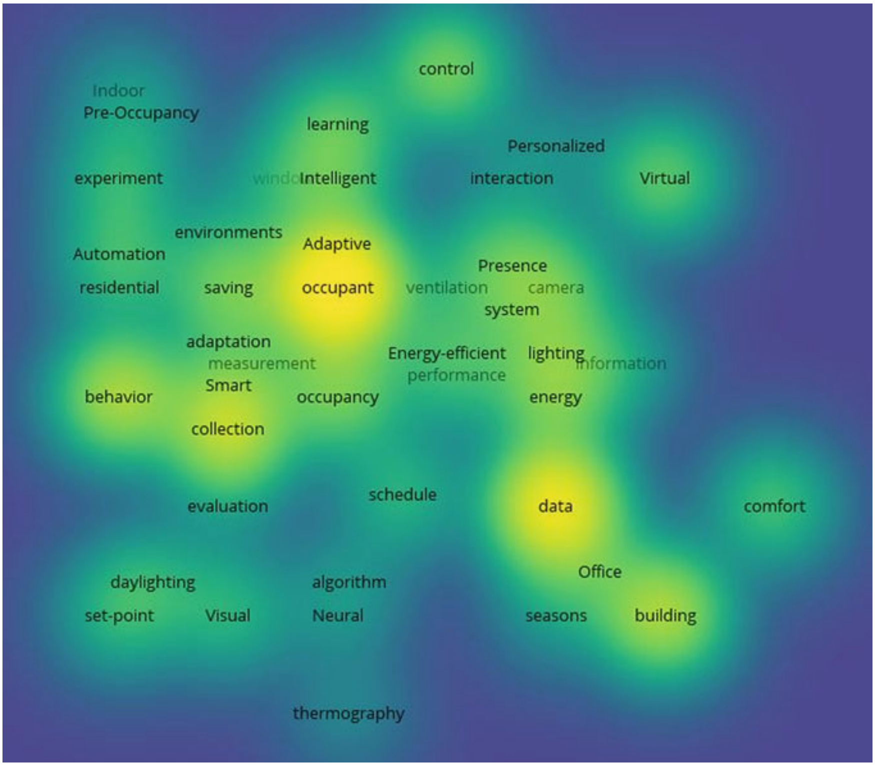

Fig. 2 Occurrence of keywords

of occurrence. Moreover, the proximity of the words to each other indicates that they were used together more often.

3 Review Results

3.1 Identification of Data Collection Approaches

In this section, the papers were analyzed based on two criteria, namely (1) Data collection requirements of OCCs, which just focuses on the type of information needed for OCC research, and (2) Methods/tools used for data collection in OCC research. Both sections have three similar sub-categories pertaining to each criterion, namely 1—Occupants interactions with building systems, 2—Indoor/outdoor environment: (to identify triggers of occupant interactions), 3—Occupants preferences. Figure 3 shows an overview of different categories analyzed in this section.

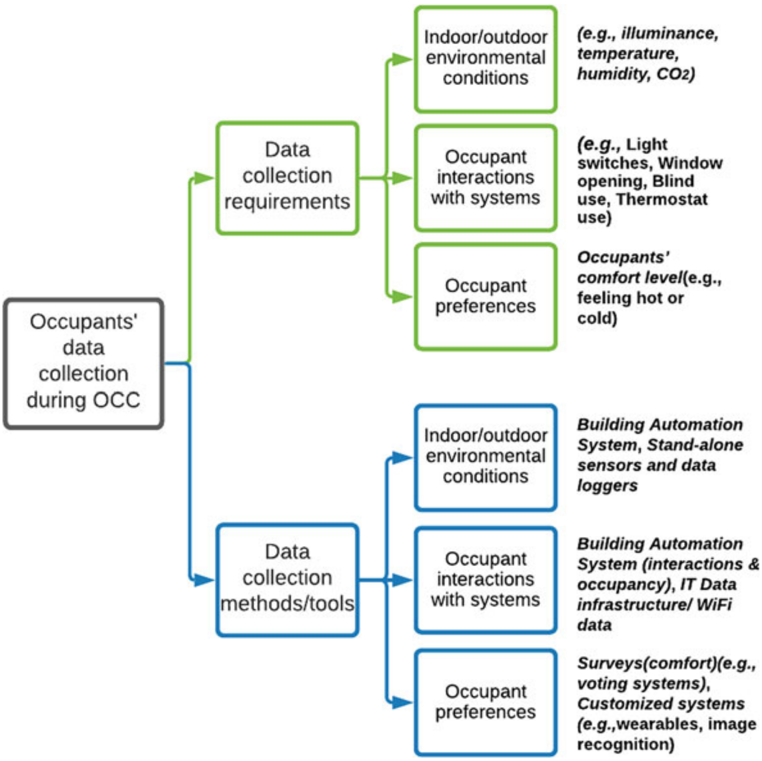

Fig. 3 Occupants' data collection during OCC

3.1.1 Data Collection Requirements for OCCs

In OCC research, it is necessary to obtain information about occupants' interactions with building systems (e.g., thermostats, light switches, and windows/blinds) and occupants' preferences (e.g., occupants' comfort level). Moreover, triggers of occupant interactions based on indoor and/or outdoor environmental parameters are needed. For instance, [9, 39] identified environmental conditions (e.g., indoor/outdoor temperature and relative humidity) at which occupants' interactions with building systems take place (e.g., thermostats presses, windows/blinds opening/closing, etc.). In Table 2, the different categories of data collection requirements are summarized.

3.1.2 Data Collection Methods/tools for OCCs

Many researchers utilized indoor and/or outdoor environmental measurements to identify triggers of occupants' interaction with building. Collecting this data typically

Table 2 Categories of data collection requirements

Data type	Description		Example
Indoor/outdoor environment	Triggers of occupant interactions		Indoor/outdoor temperature
			Illuminance
			RH
			Sounds/noises
			Air velocity/circulation
			Solar radiation
			Smell
			visual view
Occupants interactions	Action		Occupancy
			Thermostat adjustment
			Window status (on/off/stage)
			Blind status (on/off/stage)
			Door status (on/off)
			Lighting status (on/off/dim)
			Ceiling fan status (on/off/stage)
			Portable heater status (on/off/stage)
			Computer status (on/off)
Occupants preferences	Occupant demographic and contextual information	Attributes	Gender
			Age range
			Country
		Attitudes	Comfort preference (thermal/IAQ/visual)
			Energy use style
		Proxy	Wi-fi APs
			CO_2 concentration
	Occupants physiological information		Facial recognition/image recognition
			Emotions
			Heart rate/skin temperature/vascular analysis
Other	Occupancy		Presence/status
			Count

(continued)

Table 2 (continued)

Data type	Description	Example
		Location

relied on 1—Building Automation systems (e.g., temp., relative humidity (RH), valve and damper positions…etc.) and/or 2—Stand-alone sensors and data loggers.

Collecting occupant-related information, on the other hand, either focused on analyzing building occupancy (i.e., occupancy status, arrival/departure times, occupant counts) or their interactions with building systems (e.g., Light switches, SP changes, Window use…etc.). Several approaches were presented in the literature for occupancy detection, which are summarized in Table 3 adopted from [41]. On the other hand, data collection of occupant-building interactions typically relied on existing BAS infrastructure or installing additional stand-alone sensing infrastructure (e.g., window contact sensors, blinds position, time-laps cameras to monitor shade positions).

Table 3 Methods for occupancy detection

Method	Example
Motion sensor	PIR [13, 14]
	Lighting switch sensor [10]
	Pressure sensor [27, 28]
	Ultrasonic sensor [43]
Vision-based technology	Camera [6]
	image-processing occupancy sensor [7]
RF-based technology	RFID [29]
	Bluetooth [12, 18]
	Wi-Fi [5, 12]
Virtual sensors	PIR, pressure, and keyboard and mouse sensors, GPS location and Wi-Fi connection from Wi-Fi hotspots [11, 46]
Multi-sensor networks	Wi-Fi and BLE [23]
	CO2 magnetic reed switches, and PIR sensors [31]
	IMU, Wi-Fi, humidity, and illuminance sensors [21]
	Keyboard and mouse activity, webcam, microphone, PIR, temperature, RH, light, proximity sensors, and pressure mat [47]
	Smart Door (LDR and ultrasonic Sensors) [34]
	Contact closure, PIR, and CO2 sensors [33]
	PIR, pressure, and acoustic sensors [35]
	PIR, CO2, RH, temperature, air velocity and globe thermometer [36]

Fig. 4 Collection of occupants' data using surveys integrated into apps [22]

Directly collecting data on occupant preferences has been achieved using comfort surveys, which have either been manually administered [8, 24, 25] or automated using mobile applications for continuous data collection (e.g., voting systems). For example, Jayathissa et al. [22] collected thermal, visual, and aural feedbacks from occupants using apps that can be installed on participants' cellphones as shown in Fig. 4. Other studies employed customized systems such as wearables to extract information regarding occupants' preferences and comfort levels by measuring and analyzing their actions and body parameters (e.g., skin temperature, facial recognition) [2, 16, 17].

3.2 Novel Data Collection Approaches/Experimental Set Ups

Research efforts are shifting towards acquiring a deeper understanding of occupant comfort, health, and well-being in the built environment. Hence, new data collection attempts are focusing on methods to gather more data, more frequently, and less intrusively. As a result, the use of novel data acquisition approaches/experimental set ups has been increased in the last few years. The experimental set up for OCC data collection can be an existing building (for data collection or implementation), experimental/laboratory-based (e.g., mock-up spaces), or Virtual/Augmented Reality (VR). One advantage of the latter is providing more control over experimental settings (e.g., controlling the exact amount of light, glare, etc.) while only manipulating one variable of interest. More details about these alternative data collection approaches are provided below.

3.2.1 Experimental/laboratory-Based Studies (e.g., Mock-Up Environments)

In this approach, researchers extracted information from occupants with aid of cameras and/or wearables (e.g., glasses, shoe insole, wrist pad) in mock-up environments [20, 30, 44, 45]. Extracted information included physiological aspects (e.g., skin temperature, vascular territories/blood vessels analysis) [15, 42] or about location and status of body parts (e.g., facial status and emotions, eye location)

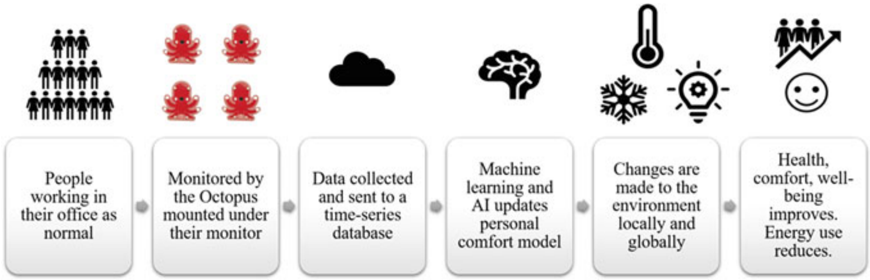

Fig. 5 Facial action unit (FAU) data collection method [3]

[3]. Based on these data, analysis of occupants' preferences and interactions were carried out. For instance, Allen et al. introduced a data collection method named Facial Action Units (FAU) which is summarized in more detail in Fig. 5. A motion detecting surveillance kit (i.e., Raspberry Pi Zero W, running MotionEyeOS, and a Pi camera) is utilized to record occupants with a timestep of 5 min and with rate of 5 frames/second (fps). These videos were then uploaded to the cloud, where they were automatically processed with OpenFace (i.e., a FAU software), and then deleted for privacy concerns. FAUs are the fundamental actions of facial individual muscles or groups of muscles. OpenFace refers to a set of facial muscle movements that correspond to a displayed emotion. It analyzed these videos for facial landmark detection, head pose estimation, facial action unit recognition, and eye-gaze estimation, which provided information about occupants' emotions, and then their comfort levels and preferences. Finally, overall satisfaction of the occupants was analyzed based-on different scales such as mental well-being scale, work engagement scale, and satisfaction with Indoor Environmental Quality (IEQ) [3]. Although the videos were deleted after analysis, several privacy concerns about this approach were raised.

3.2.2 Virtual or Augmented Reality (VR)

In this approach, the participants interact with building systems (e.g., light switches, blinds, etc.) in a virtual environment, and their actions and preferences are collected. For example, Kim et al. investigated the effect of different design features and operational strategies on occupant comfort and interaction with building systems [26], as shown in Fig. 6. Immersive Virtual Environments (IVEs) provide more control over the variables of interest and eliminate the issues related to space availability. Furthermore, it eliminates the costs, and duration associated with experimental implementation.

Fig. 6 Use of VR in OCC research [19]

4 Conclusion

Choosing the best occupants' data collection method for different OCCs can be challenging because of the various factors involved. However, understanding the main limitations of the existing data collection approaches can be very helpful. Therefore, the main shortcomings of the afore-mentioned methods are summarized in Fig. 7 and discussed in more details below.

In many of the identified OCC research studies, it was essential to install additional sensors and/or data acquisition equipment, which are costly and require regular maintenance. As a result, previous studies were mostly limited to a few rooms for periods ranging from a few hours to a few months at most. Furthermore, many data collection approaches rely significantly on the Building Management Systems (BMS), while not all buildings have extensive BMS with lots of instrumentation. Therefore, these afore-mentioned methods may be only utilized in certain types of buildings. Moreover, previous studies were mostly carried out in office or academic buildings, and the location of these buildings was mainly limited to North America, Europe, and few in East Asia. As a result, existing research is not comprehensive and universal, which raises concerns about the representativeness of their results. To address this issue, innovative approaches that rely on the increase in smart metering infrastructure and connected thermostats can enable data collection at a much wider scale.

Furthermore, in many previous OCC studies, participants were aware that they are being monitored, causing them to potentially change their normal behavior (i.e.

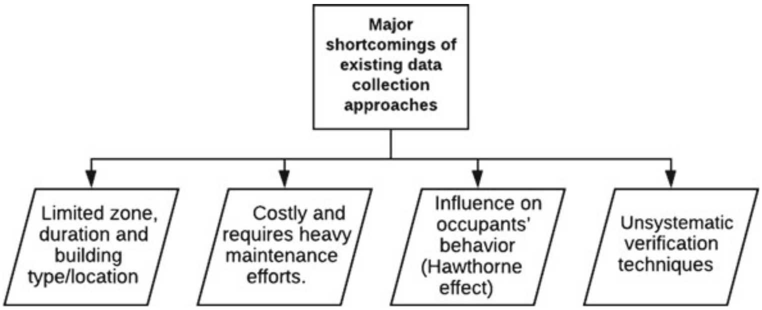

Fig. 7 Major shortcomings of existing data collection approaches

the Hawthorne effect [32]). However, previous studies suggested this issue tends to be reduced in longer-term studies [19]. Finally, most of the identified studies relied on unsystematic verification techniques. There was no practical performance evaluation of these sensing methods, or they generally lacked a rigorous and standardized Measurement and Verification (M&V) procedure. Therefore, more research is needed to standardize the evaluation of OCC performance for improving both energy efficiency and occupant comfort.

Acknowledgements This research was supported by the Natural Sciences and Engineering Research Council (NSERC) Alliance Grant # ALLRP 552694—20 in collaboration with Brainbox AI Inc. This work was also developed thanks to the excellent research networking provided by IEA EBC Annex 79 "Occupant-Centric Building Design and Operation".

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Impact Analysis of Covid-19 Pandemic on Construction Employment in the United States

Arkaprabha Bhattacharyya and Makarand Hastak

1 Introduction

The outbreak of COVID-19 pandemic has brought unprecedented effects on the U.S. economy. The U.S. Bureau of Economic Analysis (BEA) has reported that the U.S. economy witnessed a 31.4% (annual rate) decrease of real GDP in the second quarter of 2020. However, in the third quarter as the business started reopening, the real GDP bounced back and reported a growth of 33.4% [8]. COVID-19 data preserved by Johns Hopkins University shows that the number of confirmed cases started surging in March 2020 [17]. On March 13, 2020 President Trump declared the COVID-19 pandemic as a national emergency [20]. At the end of March 2020, 42 states which covers 94% of the U.S. population were under stay-at-home order [25]. Restrictions imposed by the state governments on travel, gatherings, leisure etc. to contain the virus had a colossal effect on U.S. employment. The monthly employment situation news released by the U.S. Bureau of Labor Statistics (BLS) has recorded a sharp decrease of non-farm payroll employment by 701,000 in March 2020. Among the industries, leisure and hospitality suffered the maximum consequence. The other industries that suffered notable loss are health care and social assistance, professional and business services, retail trade, and construction [9].

Ogunnusi et al. [24] have investigated the effects of COVID-19 pandemic on construction industry. They have adopted a survey-based approach. The study has found that the lockdown due to the pandemic has affected the procurement of built assets and construction industry at large. Afkhamiaghd and Elwakil [4] have developed a model of coronavirus spread in the construction industry. They have found that the factors like quantity of work, area of the job site, and daily output of the crew influence the spread of the virus. Gamil and Alhagar [18] have also investigated

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S. Walbridge et al. (eds.), *Proceedings of the Canadian Society of Civil Engineering Annual Conference 2021*, Lecture Notes in Civil Engineering 247,
https://doi.org/10.1007/978-981-19-0968-9_33

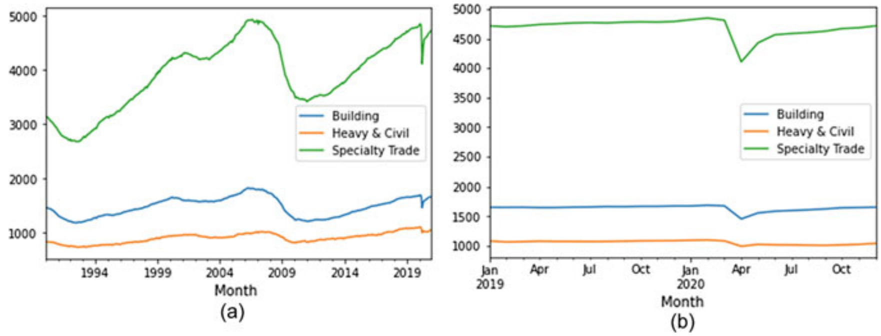

Fig. 1 Historical construction employment in thousands **a** between 1990 and 2020, **b** between 2019 and 2020

the impact of COVID-19 pandemic on construction industry. They have interviewed ten subject matter experts and surveyed 129 construction practitioners. They have found that the impacts were conspicuous in project suspension, labor shortage, job loss, cost overrun, and time overrun. Other studies relating COVID-19 pandemic and construction industry can be found in Bsisu [14], Al Amri and Marey-Pérez [6].

This paper presents the impacts of COVID-19 pandemic on construction employment. The impact has been assessed at subsector level. The U.S. construction industry is comprised of three subsectors: building, heavy and civil, and specialty trade. Figure 1 shows the variation of employment in three subsectors. It can be seen specialty trade employs the most among the subsectors, which is followed by building, and heavy and civil. The paper answers two research questions (1) how much construction employment has changed due to pandemic and (2) whether the change was uniform across the subsectors or not.

The impact of COVID 19 pandemic on employment has been defined as the difference between the expected employment following pre-pandemic employment trend and the observed actual employment. For conducting the analysis, this paper has adopted intervention analysis method. Intervention analysis was first proposed by Box and Tiao [13] to estimate the change in the pollution in downtown Los Angeles due to two major events. Sharma and Khare [27] have conducted intervention analysis to gauge the impact of a legislation introduced by the Government of India in 1996 on the CO emission by different vehicles. Seong and Lee [26] have used exponential smoothing based intervention analysis to analyze the impact of 9/11 terrorist attack on U.S. air traffic and COVID-19 pandemic on people's movement in Seoul. Historic employment data of the subsectors between January 1990 and February 2020 were used to forecast the expected employment in absence of COVID-19 pandemic. For forecasting purpose, the paper has used Autoregressive Integrated Moving Average (ARIMA) technique. The research has found that construction employment was down by 5.5 million between March 2020 and December 2020. This was further used in an Analysis of Variance (ANOVA) test to answer the second question. It has been found that the impact has not varied across the subsectors. The outcomes of the paper can be used by the policy makers to understand the broader implications of the construction employment change since industries are interdependent between themselves [11] and prepare subsector specific recovery plan.

2 Research Methodology

The methodology is shown in Fig. 2. The paper has adopted Intervention Analysis using Autoregressive Integrated Moving Average (ARIMA) method for estimating the impact of COVID-19 pandemic on construction employment. For that, seasonally adjusted employment data for the 3 subsectors (building, heavy and civil, and specialty trade) were collected from BLS [10]. Since, construction employment is highly seasonal [19], seasonally adjusted data have been used to overcome the impact of seasonality. For Intervention Analysis, February 2020 was considered as the point of intervention since National Bureau of Economic Research (NBER) considers March 2020 as the first month of recession [22, 23]. There are three primary steps in the intervention analysis [7]:

(1) Historical data between January 1990 and February 2020 were used to determine the ARIMA model for the dataset.
(2) The selected model was used to forecast the expected employment between March 2020 and December 2020.
(3) The change of employment was calculated for each month between March 2020 and December 2020.

The changes were calculated for each subsector and expressed as a percentage of the expected employment to understand the percentage change. Then, the percentage change for all 10 months were utilized to conduct an Analysis of Variance (ANOVA) Test to check if the three subsectors were affected equally or not.

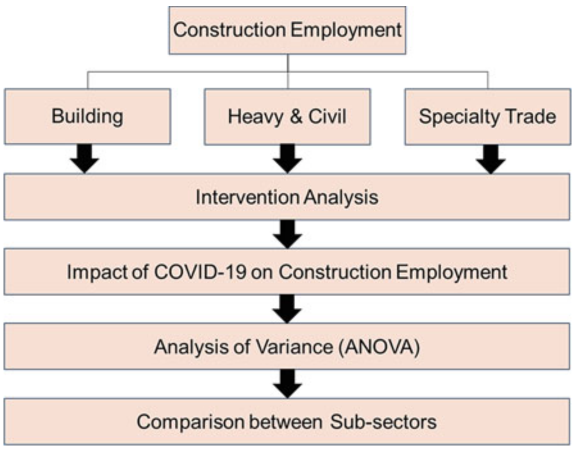

Fig. 2 Research methodology

3 Intervention Analysis

For intervention analysis Autoregressive Integrated Moving Average (ARIMA) method has been adopted. Historic employment data between January 1990 and December 2020 were collected for all three subsectors. Data till February 2020 were used to forecast the expected employment for all ten months between March 2020 and December 2020 using ARIMA method. The descriptive statistics are shown in Table 1.

An ARIMA model is represented as (p, d, q) [12] where, "p" is the order of autoregression (AR), "d" is the order of differencing required to make the dataset stationary, "q" is the order of moving average (MA). First, Augmented Dickey-Fuller (ADF) Test was performed on the dataset. In an ADF test, the presence of non-stationarity (null hypothesis) is tested against the absence of non-stationarity (alternate hypothesis). The results of the ADF test for the three datasets can be found in Table 1. All three datasets resulted a p-value over 0.05 which is the critical p-value. This provides sufficient evidence in favor of the null hypothesis. Therefore, the datasets had to be differenced to make them stationary. The three datasets: Building, Heavy and Civil, and Specialty Trade required two, one, and one differencing respectively to make them stationary thus making 'd' value two, one, one respectively for the three datasets. Once the 'd' values were identified, a grid search was performed to find the optimal values of 'p' and 'q'. In the grid search the possible ranges for 'p' and 'q' were provided. Then ARIMA models with all possible combinations of 'p', 'd', and 'q' were created and the models with the best performance for all three subsectors were selected for further analysis. For assessing the model performance, Akaike Information Criterion (AIC) [5] was adopted. The models with the lowest

Table 1 Descriptive statistics of the dataset (Jan 1990—Feb 2020)

	Building	Heavy and civil	Specialty trade
Mean (thousands)	1467.7	891.4	3893.5
Std (thousands)	179.4	91.7	648.0
Min (thousands)	1176.0	722.4	2667.3
25% (thousands)	1303.6	819.2	3450.6
50% (thousands)	1472.0	902.5	3987.2
75% (thousands)	1604.2	953.4	4389.4
Max (thousands)	1822.4	1098.9	4931.3
ADF test p-value	0.053	0.525	0.131

Table 2 Model performance comparison

Building		Heavy and civil		Specialty trade	
Model	AIC value	Model	AIC value	Model	AIC value
(0, 2, 1)	2388.47	(3, 1, 4)	2373.72	(3, 1, 4)	3072.39
(0, 2, 3)	2388.49	(4, 1, 4)	2377.33	(4, 1, 4)	3075.22
(2, 2, 1)	2388.87	(4, 1, 3)	2378.34	(2, 1, 2)	3079.43
(0, 2, 2)	2388.98	(2, 1, 2)	2381.62	(1, 1, 3)	3079.52
(1, 2, 1)	2389.29	(1, 1, 3)	2381.91	(1, 1, 2)	3079.72

AIC value were selected for forecasting purpose. For all three datasets ‘p’ and ‘q’ were varied between [0, 4]. This creates 5^2 or 25 possible combinations for ‘p’ and ‘q’. For brevity, the performance of the 5 best models is shown in Table 2.

Table 2 shows that ARIMA (0, 2, 1), ARIMA (3, 1, 4), and ARIMA (3, 1, 4) had the best fit for the building, heavy and civil, specialty trade dataset, respectively. So, they were used in forecasting the expected employment based on the historic trend. This approach of estimating the impact of COVID-19 pandemic assumes that the employment would have followed the same trend if there were no COVID-19 pandemic. Table 3 shows the change of construction employment for the three subsectors. The change has been calculated as difference between expected employment following the historical trend and actual employment observed due to COVID-19 pandemic. It can be seen from Table 3 that the change was maximum in April 2020. During this time, most of the states imposed stay-at-home orders to contain the spread of the virus. The change reduced as the year progressed and the restrictions were lifted. The analysis indicates that COVID-19 pandemic brought down construction employment by 5.5 million between March 2020 and December 2020. Among the three subsectors, the specialty trade had the maximum employment change (3.5 million), followed

Table 3 Estimated construction employment change in thousands due to COVID-19 pandemic

Month	Building	Heavy and civil	Specialty trade	Total
Mar-2020	17	16	49	82
Apr-2020	243	107	773	1123
May-2020	147	80	467	695
Jun-2020	123	90	347	559
Jul-2020	117	92	340	549
Aug-2020	109	99	341	549
Sep-2020	101	105	331	537
Oct-2020	86	97	301	484
Nov-2020	86	89	301	476
Dec-2020	87	77	282	446
Total	1116	851	3532	5500

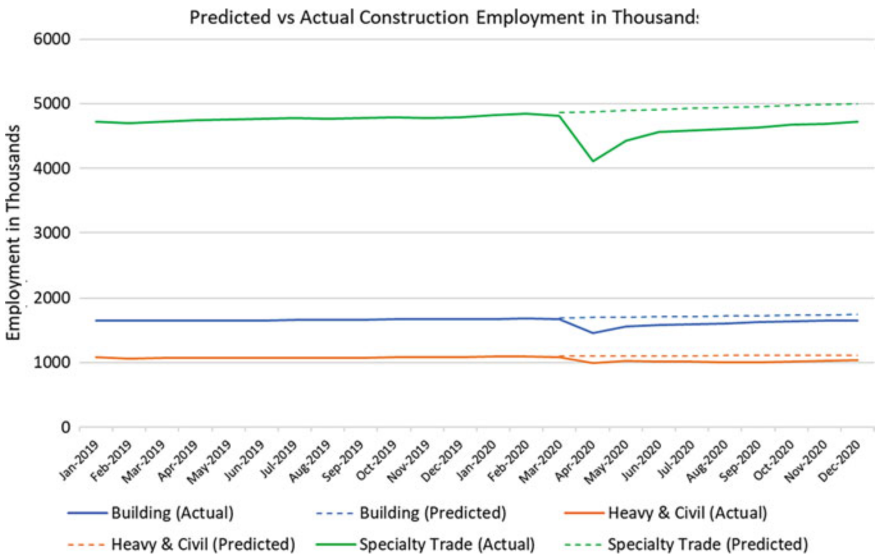

Fig. 3 Outcomes of intervention analysis

by building (1.1 million), and heavy and civil (0.9 million). Figure 3 visualizes the outcomes of the paper. The dotted lines represent the expected employment in three subsectors if pre COVID-19 pandemic trends continued while the solid lines show the actual employment numbers.

4 Analysis of Variance

The second question this paper intended to answer was whether the impact was uniform across the three subsectors or not. It can be seen in Table 3 that specialty trade had the maximum employment change. But the employment generated by the three subsectors are significantly different from each other. Among the three subsectors, specialty trade creates 62% of the total construction employment, building sector creates 24%, and heavy and civil sector creates remaining 14% of the construction employment. The effect of this is not reflected in the results in Table 3. Therefore, the changes were converted into percentages. The percentage employment change was calculated as Eq. 1.

$$PercentageEmploymentChange = \frac{PredictedEmployment - ActualEmployment}{PredictedEmployment} \quad (1)$$

Table 4 Percentage employment change due to COVID-19 pandemic

Month	Building (%)	Heavy and civil (%)	Specialty trade (%)
Mar-2020	1	1	1
Apr-2020	14	10	16
May-2020	9	7	10
Jun-2020	7	8	7
Jul-2020	7	8	7
Aug-2020	6	9	7
Sep-2020	6	9	7
Oct-2020	5	9	6
Nov-2020	5	8	6
Dec-2020	5	7	6
Average	6.5	7.7	7.2

Table 4 shows the percentage employment change. For instance, in April 2020, the employment in specialty trade was down by 16%. This implies that the actual employment in specialty trade was 84% of what was expected had the employment trend before the pandemic continued. The average percentage employment change was maximum for heavy and civil subsector, followed by specialty trade, and building subsector.

The next step was to investigate whether this change is statistically significant or not. For that, the paper has adopted one way analysis of variance (ANOVA) test. The detailed procedure for ANOVA test can be found in Devore [16]. The null hypothesis claims that the three subsectors had faced equal impact of COVID-19 pandemic ($H_0 : \mu_1 = \mu_2 = \mu_3$, where $\mu_1, \mu_2, and \mu_3$ are the average percentage employment change in building, heavy and civil, and specialty trade subsector, respectively). Thus, the difference in average percentage change in employment in three subsectors is insignificant. The alternate hypothesis contradicts this claim ($H_a : \mu_1 \neq \mu_2 \neq \mu_3$). Table 5 shows the outcomes of the ANOVA test.

The test results can be obtained in terms of F value and P-value which are 0.34 and 0.72, respectively. The test was performed at 5% level ($\alpha = 0.05$). For $\alpha = 0.05$, the critical value of F (F crit) is 3.35. Since the F-value (0.34) is less than 3.35, it can be inferred that the null hypothesis is true. This indicates that the three subsectors were affected equally.

Table 5 ANOVA results

Source of variation	SS	df	MS	F	P-value	F crit
Between groups	0.0007	2	0.0003	0.3374	0.7166	3.3541
Within groups	0.0278	27	0.0010			
Total	0.0285	29				

5 Discussion

The paper has found that between March 2020 and December 2020, the construction employment was down by an estimated 5.5 million with 20% of it taking place in April 2020 only. In the initial stages of the pandemic, states like Michigan, New York, Pennsylvania, and Washington along with some of the major cities like Boston, Austin, San Francisco decided to shut down all construction projects [21]. On March 19, 2020, the federal government issued an order that allowed workers in the critical infrastructure industry to continue work and maintain their normal schedule [15]. While the order listed industries for which construction is absolutely essential, it did not explicitly mention construction as an essential service [1]. In March 2020, the Associated General Contractor of America (AGC) conducted a survey of their members regarding the ongoing projects and the projects that are expected to start in 30 days. The survey outcomes show that owners, government agency and officials directed to halt 28 and 11% of the ongoing and upcoming projects, respectively [2]. The same survey conducted in June 2020 shows that only 32% of the owners did not ask to halt or cancel any ongoing and upcoming works. Rest 68% either halted or cancelled. Out of the 551 respondents of the survey 25% indicated that they have furloughed or terminated their employees on or before May 2020. AGC found that the stoppages are attributed more to the owner concerns than government orders [3].

6 Conclusion

COVID-19 pandemic has posed an unprecedented challenge on the U.S. economy. Construction as an industry has also suffered from the recession triggered by COVID-19 pandemic. In this paper, the impact of COVID-19 pandemic on construction employment has been presented. The paper has adopted ARIMA method to perform intervention analysis. Historic employment data of three constituting subsectors of construction industry: building, heavy and civil, and specialty trade were collected between January 1990 and December 2020. Data till February 2020 were used to forecast the employment between March 2020 and December 2020 using ARIMA technique. Three different ARIMA models were created for three subsectors. The forecasting outcomes were used in calculating the employment change due to COVID-19 pandemic. It has been found that the cumulative employment in three subsectors was reduced by 5.5 million due to the pandemic. The forecasting outcomes were further used to perform an ANOVA test. The ANOVA outcomes indicate that there is no significant difference among the subsectors in terms of percentage change in employment. In the future, research will be conducted at the state level to understand how the impacts have changed from one state to another. This might help to gain insights regarding the best practices that could help making construction industry more resilient to the exogenous shock.

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The Applicability of the Two-Fluid Model to Simulate Soil Internal Fluidization Due to Pipe Leakage

A. Ibrahim and M. Meguid

1 Introduction

Internal soil fluidization and erosion can happen in the vicinity of leaking buried pipes due to local pressure increase and rapid water flow within the surrounding soil. When fluidized, the soil loses some or all of its shear strength (i.e., liquefied) due to the increase in pore water pressure. This can compromise the soil integrity, strength and ultimately leads to volume loss and the formation of sinkholes [1, 15]. Characterizing and predicting internal fluidization of soils can be particularly challenging considering the complex underlying physics that govern fluidization [7]. These physics involve the interaction mechanisms, momentum transfer and force balance between soil particles and water, or other fluids [27]. This type of analysis has been widely adopted in fluidized beds, where fluidization is induced by gas or liquid injection through an opening [8, 19, 22]. In ground engineering and earth structure, with less controlled environment than this of fluidized beds, the analysis becomes more complex as the properties of soils such as cohesion and particle size variability come to play a major role [21, 28]. Furthermore, if a hydraulic transient is to occur in a compromised leaking pipe, more complex interactions are to happen as the pressure wave travels back and forth across the system.

Analyzing internal fluidization requires access to information related to the micromechanics of the system and resolving the particle–fluid interaction. Several attempts have been made to investigate these interactions experimentally [2, 25], numerically [7] and using simplified analytical models [18, 26]. Given the limited

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S. Walbridge et al. (eds.), *Proceedings of the Canadian Society of Civil Engineering Annual Conference 2021*, Lecture Notes in Civil Engineering 247,
https://doi.org/10.1007/978-981-19-0968-9_34

flexibility of experimental and analytical solutions in obtaining microscale information and dealing with a wide range of initial and boundary conditions, numerical analysis is mostly adopted. The two most common approaches are pure continuum analysis and coupled discrete-continuum analysis. In pure continuum analysis, the solid and fluid phases are treated as a single continuum with collective properties that account for the presence of both phases (i.e., a mixture). Alternatively, the two phases are interpreted as inter-penetrating continua each representing a single phase such as the case of the Two-Fluid Model (TFM) [3, 10, 16]. On the other hand, in coupled discrete-continuum analysis the solid phase receives a discrete Lagrangian treatment while the fluid phase is considered as a continuum. Examples for this type of analysis involve the coupled Discrete Element Model-Computational Fluid Dynamics (DEM-CFD) [23] and Discrete Element Model-Lattice Boltzmann Model (DEM-LBM) [6].

Although utilizing discrete methods such as DEM-CFD allows for a relatively more accurate representation of the soil–water coupling compared to continuum-based approaches, it comes at a high computational cost [12]. On the contrary, coupled continuum modelling such as the TFM is much more computationally feasible with code execution time of approximately 7% of this of CFD-DEM [11]. Thus, it allows for analyzing larger and more realistic systems and producing results than can be incorporated into conventional analysis needed for design and risk assessment. The application of the TFM, however, has so far been limited to a few cases in simulating sediment transport and riverbed morphology [4, 5]. The model's performance is yet to be tested in dealing with earth structures where soils are densely packed and quasi-static flow conditions are most likely to be dominant.

In this study, we aim to explore the potential of the TFM to simulate internal fluidization around leaking pressurised pipe (Fig. 1a). The test case consists of a buried pressurised pipe with an aperture, through which, a water jet is released into the overlying sand layer leading to internal fluidization that can lead to the formation of a water-filled cavity (Fig. 1b). We investigate the ability of the model to capture the extent of the fluidized zone and the associated changes in pore water pressure.

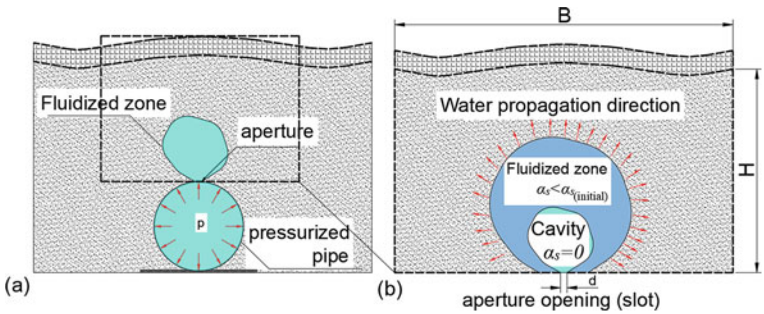

Fig. 1 Schematic diagrams for the onset of fluidization: **a** Illustration of the formation of internal fluidization in the vicinity of a leaking pipe, **b** A conceptual representation of the fluidization parameters around the aperture

Emphasis is placed on identifying the drawback and limitations of the TFM approach in analyzing soil fluidization caused by water leakage in subsurface structures.

2 Numerical Analysis

The TFM used in this study was developed following the local volume-averaging technique proposed by Anderson and Jackson [3]. In this model, the particulate phase is considered as a fluid-like continuum with equivalent pressure and shear stress flow parameters that reflect the granular behaviour of solids. Thus, the core of this model is the constitutive relationships (closures) used to obtain these parameters. Significant developments to these closures have been made since they were early presented by Anderson and Jackson [3] such as the Kinetic Theory of Granular Flow (KTGF) [10, 13, 17, 24] and granular rheology [5, 20]. The governing equations for the TFM consist of the locally averaged continuity and momentum equations. The conservation of mass for both phases can be written as [4]:

$$\frac{\partial \rho^f \alpha^f}{\partial t} + \frac{\partial \rho^f \alpha^f u_i^f}{\partial x_i} = 0, \tag{1}$$

$$\frac{\partial \rho^s \alpha^s}{\partial t} + \frac{\partial \rho^s \alpha^s u_i^s}{\partial x_i} = 0. \tag{2}$$

where α^f and α^s are the volume fractions of both fluid and solid phases such that $\alpha^f + \alpha^s = 1$, ρ^f and ρ^s are the mass densities and u_i^f and u_i^s are (i^{th}) components the cell-averaged velocities of fluid and solid phases, respectively (i.e., u_x, u_y or u_z in cartesian coordinates). Similarly, the conservation of momentum is written as:

$$\begin{aligned}\frac{\partial \rho^f \alpha^f u_i^f}{\partial t} + \frac{\partial \rho^f \alpha^f u_i^f u_j^f}{\partial x_i} =& -\alpha^f \frac{\partial p}{\partial x_i} + \alpha^f f_i + \alpha^f \rho^f g_i \\ &+ \frac{\partial \tau_{ij}^f}{\partial x_j} - \alpha^f \alpha^s K\left(u_i^f - u_i^s\right),\end{aligned} \tag{3}$$

$$\begin{aligned}\frac{\partial \rho^s \alpha^s u_i^s}{\partial t} + \frac{\partial \rho^s \alpha^s u_i^s u_j^s}{\partial x_i} =& -\alpha^s \frac{\partial p}{\partial x_i} + \alpha^s f_i + \alpha^s \rho^s g_i \\ &- \frac{\partial \overline{p}^s}{\partial x_i} + \frac{\partial \tau_{ij}^s}{\partial x_j} + \alpha^f \alpha^s K\left(u_i^f - u_i^s\right).\end{aligned} \tag{4}$$

where p is the fluid pressure, f_i and g_i are the external and driving body forces and the gravitational acceleration, τ_{ij}^f is the shear stress tensor of the fluid phase, τ_{ij}^s and $\overline{p}^s$ are the shear and normal stresses of the solid phase, and K is the drag parameter. The last term of the right-hand side of Eqs. (3) and (4) represents the drag force between the two phases associate with particle–fluid interaction, hence it appears in opposite signs such that Newton's third law of motion is not violated.

The solid granular phase is essentially discrete, such that macro-scale or domain-averaged pressure and shear forces are determined from the collective forces acting on individual particles. However, the continuum representation of the solid phase in Eqs. (2) and (4) does not allow for direct discrete treatment of the solid particles. Thus, closures are needed to obtain the equivalent granular pressure and shear stresses as cell-averaged values. In this study, the closures obtained from the Kinetic Theory of Granular flow are adopted [9, 10]. The solid granular pressure, $\overline{p}^s$, consists of two components: permanent contact pressure, p^{ff}, and shear induced pressure p^s [14]:

$$\overline{p}^s = p^{ff} + p^s \tag{5}$$

where the permanent contact component is expressed as:

$$p^{ff} = \begin{cases} 0 & \alpha^s < \alpha_{\min}^{Fric}, \\ Fr \frac{(\alpha^s - \alpha_{\min}^{Fric})^{\eta_0}}{(\alpha_{max} - \alpha^s)^{\eta_1}} & \alpha^s \geq \alpha_{\min}^{Fric} \end{cases} \tag{6}$$

where Fr, η_0 and η_1 are empirical parameters that take the values of 0.05, 3 and 5, respectively [5]. $\alpha_{\min}^{Fric}$ is the minimum solid fraction considered for interparticle friction to develop, for spherical particles, $\alpha_{\min}^{Fric} \approx 0.57$. and α_{max} is the maximum value of solid volume fraction. Special attention should be given to the terms in Eq. (6) to avoid diving by zero when $\alpha_{max} = \alpha^s$. This is especially critical in the case when initial settlement of solid particles is required (i.e., static condition). If the initial solid fraction value was set close to α_{max}, numerical instabilities will develop and most likely will lead to a numerical singularity. In order to avoid this, a reasonable margin should be given between the initial and maximum packing values such that the desired initial condition can be achieved without causing instabilities.

The shear-induced granular pressure depends mainly on the granular temperature of the system, Θ, the radial distribution function, g_{s0}, and the coefficient of restitution, e, where the values of the shear-induced pressure is given by Ding and Gidaspow [9]. The simulation was carried out using sedFoam solver [5] on OpenFOAM CFD platform. The solver is an isothermal incompressible version of the twoPhaseEulerFoam solver in OpenFOAM, which is a two-phase solver for solid–fluid flows. The closures of the KTGF presented herein are incorporated in the solver for pressure and shear stress estimation in the solid phase.

3 Model Validation

To test the validity of the TFM to simulate internal fluidization, we set up a numerical model to reproduce the experimental study reported by Alsaydalani [2] and the numerical study performed using Discrete Element Model-Lattice Boltzmann Model

(DEM-LBM) by Cui et al. [7]. Both studies tackle the problem of internal fluidization in a submerged sand bed subjected to a local controlled water injection that resembles water leakage from a buried pipe. One of the important reasons we chose to validate the model using the two aforementioned studies is to test the model's scalability. As opposed to CFD-DEM model, the continuum nature of the TFM allows for local mesh refinement around narrow openings and complex geometry. This can be much more computationally efficient as the need to use a large number of particles no longer exists. It is worth noting that the mean particle size for the numerical study of Cui et al. [7] is approximately 4.5 times larger than that used in the experiment to reduce the computational cost. Consequently, the slot opening size is increased to 10 times larger. Thus, the scalability of the model presented in this study is put the test to see if this limitation can be overcome by refining the computational mesh around the injection slot.

The experimental setup consists of a box filled with submerged silica sand (sand bed), while water is injected at controlled flow rates through a rectangular slot at the bottom of the box (Fig. 2). Probes to measure the excess pore water pressure are placed along the centreline of the box and connected to sight-tubes to measure the development of excess pore water pressure throughout the experiment. Snapshots of the deformation of the sand bed are taken throughout the experiment to monitor the surface heave and the extent of the fluidized zone. For the numerical simulation considered in this study, the height of sand inside the box is set to 0.3 m with two cases for average particle sizes of 1 and 4.5 mm corresponding to slot openings of 0.33 and 3 mm, respectively. A summary of the simulation parameters for both cases is shown in Table 1.

Initially, the system is set up with solids at a volume fraction of 0.55, which is lower than the desired packing prescribed in the experiment ($\alpha^s = 0.63$) to allow for interparticle forces to properly develop. Afterward, the solid particles are left to

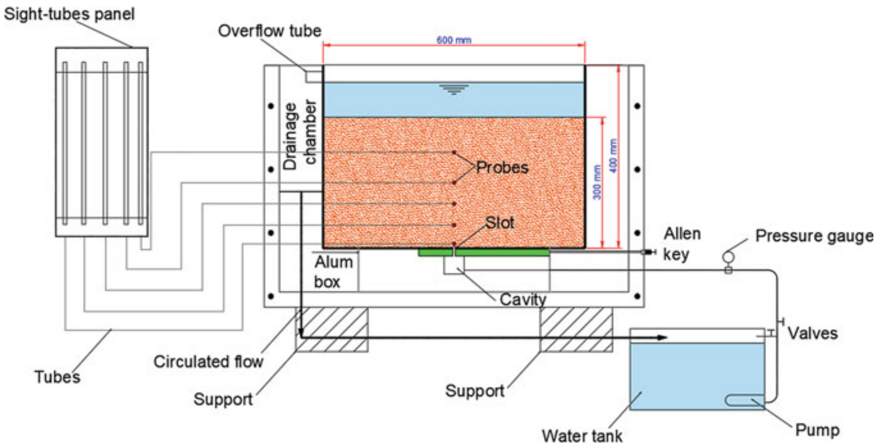

Fig. 2 A schematic of the experimental setup. Adapted from Alsaydalani [2]

settle down to the prescribed volume fraction of 0.63 such that the total height of the silica sand submerged underwater is 0.3 m. The maximum packing limit, α_{max}, is set to 0.68 such that no numerical instabilities rise from the computation of the permanent contact pressure term. Settling is left long enough (approximately 18 s of simulation time) to ensure that the system is initially static and no particle or fluid movement is happening. After the particles had settled such that the sand bed is initially at rest, water is injected through the slot at controlled flowrates. For the first simulation case used to reproduce the results reported by Alsaydalani [2], the in injection flow rates are 135.6, 235.5, 338.8, and 506 l/h. As for the second simulation case used to reproduce the DEM-LBM results reported by Cui et al. [7], the injection flow rates are 0.25, 0.5, and 0.75 l/s, which are equivalent to 900, 1800, and 2700 l/h.

4 Results and Discussion

The numerical results presented in this section focus on two aspects: (i) the development of excess pore water pressure in the vicinity of the water jet, and (ii) the deformation and mobilisation of sand particles in the sand bed. The latter involves the surface heave and the formation of cavities/fluidized zones around the location of injection. Both aspects should give insights on the model's performance regarding capturing micro and macro-scale interactions.

4.1 Pore Water Pressure

The numerically calculated excess pore water pressure values along the centreline of the box are shown in comparison to both experimental and DEM-LBM numerical results in Figs. 3 and 4. From the simulation, we observe that the excess pore water pressure value peaks at the location of the injection slot. The excess pore water pressure is then dissipated gradually until it approaches a value of zero at the surface of the sand. For both validation cases, we find that approximately 60–70% of the excess pore water pressure is dissipated in the lower 80 mm of the sand bed. Such high rate of dissipation can be referred to the high energy needed at the injection entrance to mobilize a portion of the sand mass. Above the lower 80 mm of the

Table 1 Summary of simulation parameters used by Cui et al. [7] and Alsaydalani [2]

	Solid density (kg/m^3)	Fluid density (kg/m^3)	Bed height (m)	Orifice opening (mm)	Average particle size (mm)
Experiment	2650	1000	0.3	0.33	1
DEM-LBM	2700	1000	0.3	3	4.5

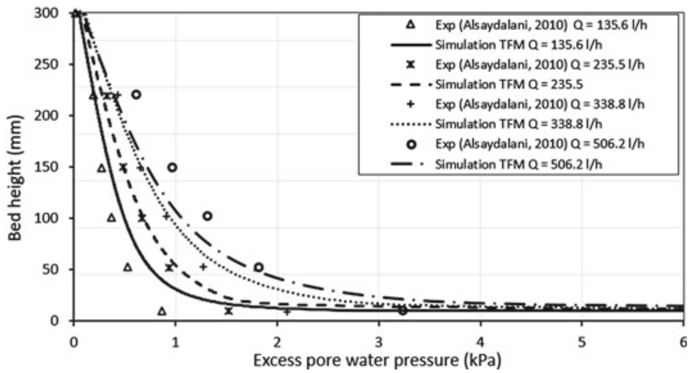

Fig. 3 Excess pore water pressure along the centreline above the injection slot for different flowrates, TFM simulation verses experimental results

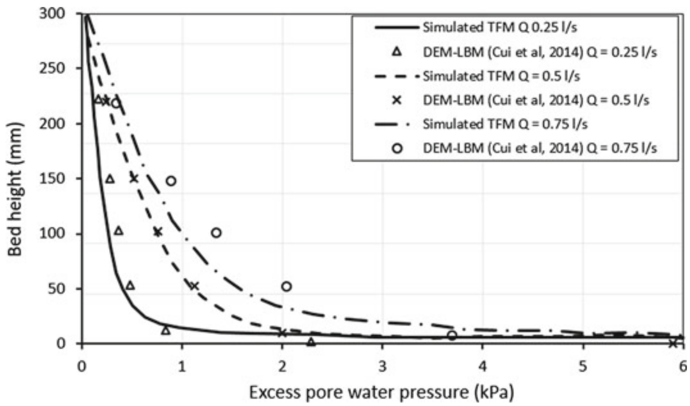

Fig. 4 Excess pore water pressure along the centreline above the injection slot for different flowrates, TFM simulation verses DEM-LBM results

sand bed, the excess pore water pressure appears to vary nearly linearly with depth, indicating a steady flow velocity. These observations align with those reported by Alsaydalani [2] and Cui et al. [7] in the sense that the inlet velocity is higher than the critical velocity, beyond which, fluidization will occur.

The results for excess pore water pressure obtained from the TFM simulations show good agreement with both experiment and DEM-LBM simulation in terms of the general trend and obtained values. The extent of mobilisation of solid particles, however, is difficult to investigate solely from the results of excess pore water pressure as it requires further investigation of the deformation of the sand bed.

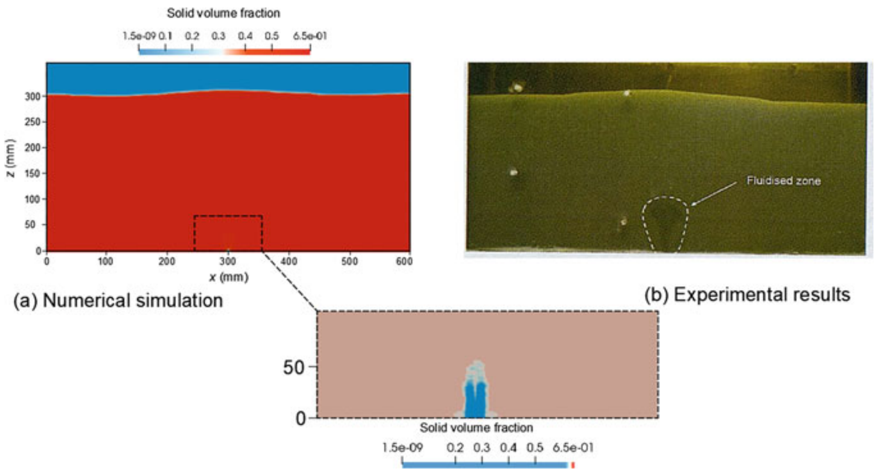

Fig. 5 A comparison between the shape and the extent of the fluidized zone and surface heave, **a** TFM simulation verses **b** experimental results from Alsaydalani [2]

4.2 Surface Heave and the Extent of Fluidization

To investigate the fluidized zones in our simulation, we look at the physical deformation of the sand bed from our simulation. As the sand surface or water above are not restrained (i.e., free surface condition), the upward driving force from injection is expected to cause heaving in the sand surface. This heave can be observed from the simulation (Fig. 5a) and shows a decent agreement with the respective photographs from the experiment (Fig. 5b). To visualise the fluidized zone around the injection slot, the colour scale representing solid volume fraction is shifted towards the far end of initial packing to display any possible mobilisation that could have happened (lower panel of Fig. 5). The extent of the fluidized zone, although being slightly less than this from the experiment, shows a good representation of the fluidization area. Despite being mobilised, no cavities have been formed around the injection slot. This follow regime can be classified as a “static bed regime” as indicated by Cui et al. [7], where no observable cavities are generated. This regime can be most closely interpreted as seepage flow, however, a fundamental difference from seepage is that the soil matrix does not remain intact and can be subjected to changes as injection conditions change.

A thorough investigation of the solid volume fraction for different flow rates is shown in Fig. 6. It can be seen that particles are washed away in the vicinity of injection causing a reduction in the solid volume fraction of approximately 11–15% and is directly proportional to the value of flow rate. Overall, the model showed good performance in capturing the characteristics of the onset of fluidization in comparison with the available experimental and numerical results. More importantly, the execution time for the two test cases considered in this study was nearly the same, which confirms the model’s scalability. This can provide a reasonable preliminary

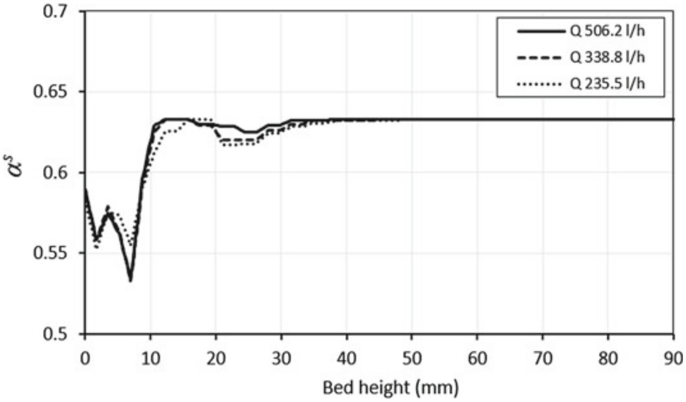

Fig. 6 Variation of the solid volume fraction along the centreline for different flow rates

assessment for the state of stresses and deformation in the vicinity of leakage and beyond. Nonetheless, the model suffers from some inherent drawbacks that should be taken into consideration.

4.3 Model Limitations

The constant particle size used in the TFM simulation may not be a good representation of the actual soil. This issue was not observed in the comparison included here mainly because of the uniform nature of sands used in the experiment and numerical simulation. However, when dealing with actual soils, a much wider range of particle size distribution is most likely to be the case. Since the model deals with cell-averaged values of porosity, pressure and shear stresses, the actual coupling behaviour will be more difficult to capture. This issue becomes more critical in gap-graded soils where smaller particles are expected to be washed away into the pores of larger particles.

5 Conclusions

In this study, we tested the potential of the two-fluid model to simulate the internal fluidization in a submerged sand bed subjected to controlled injection (leakage) flow rates. The following observations and conclusions could be identified:

1. Our simulation results showed good agreement with reported experimental and numerical results of excess pore water pressure, surface heave and fluidized zone.

2. The model could decently capture the microscale-related interactions such as local fluidization as well as macro-scale behaviour such as surface heave.
3. Some inherent drawbacks to the model are identified such as its inability to account for particle size distribution, cohesion and particle shape.
4. The mesh-based adopted simulations' accuracy might be questionable when dealing with applications that involve fragmentation or highly convective flows in general.
5. Overall, the model can be a viable tool for preliminary assessment of coupled water-soil applications.

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Preliminary Analysis of Emerging Visualization and Image Modeling Technologies for Highway Construction Inspection

Mamdouh Mohamed, Phuong Nguyen, and Daniel Tran

1 Introduction

Construction and maintenance projects, such as roadways and bridges, have displayed little productivity growth during the past two decades. Number of factors (e.g., shortage of funding) contributed to this situation. Among these factors, reliance on the conventual paper-based management processes is a critical root cause of low efficiency in construction inspection activities. The continued reliance on paper-based processes during project development and delivery impedes innovation whereas the shortage of qualified staff slows down production rates and reduces quality of the final product [1]. Previous studies show that there is a direct correlation between the digitalization rate of construction industry and productivity improvements. For instance, adopting effective practices to infuse the use of e-construction technologies and advanced automation instead of the paper based can increase productivity by 8% on average and result in cost savings up to 5% [1]. The Federal Highway Administration (FHWA) defines e-construction as a paperless construction administration delivery process. This process includes electronic submission of all construction documentation by all stakeholders, electronic document routing and approvals (e-signature), and digital management of all construction documentation in a secure environment [2]. E-inspection is a substantial part of this automated process, including electronic field data collection by inspectors, data analysis, and documentation of inspection results. There are ongoing initiatives to support e-inspection for

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S. Walbridge et al. (eds.), *Proceedings of the Canadian Society of Civil Engineering Annual Conference 2021*, Lecture Notes in Civil Engineering 247,
https://doi.org/10.1007/978-981-19-0968-9_35

transportation construction projects. For example, the FHWA's Every Day Counts (EDC) initiative focuses on employing technologies readily available to the transportation projects, including digital electronic signatures, electronic communication, secure file sharing, mobile devices, and visualization and Image modeling techniques to improve construction management processes [2].

Previous studies have examined application of different visualization and image-capturing technologies in construction projects. For instance, Okpala et al. [3] examined utilization of emerging technologies such as building information modeling (BIM), augmented reality (AR), virtual reality (VR), and image-based sensors. The study found that these technologies are not applied broadly in construction projects. Yamaura and Muench [4] conducted a study to assess the impact of mobile technology on public transportation project inspection. Results of the study indicated that project inspectors using the mobile technology system experienced higher productivity, collected and shared twice as many observations and inspection images, and improved the timeliness of daily reports. There has been an increasing number of publications concerning the visualization and image modeling technologies in the area of construction projects during the past two decades. However, limited research has focused on providing a systematic review and content analysis of published articles related to applying these technologies to transportation construction projects. Researchers need to identify implementation challenges, the current, and future application trends of these technologies to different construction operations. Further, practitioners need to a useful reference on adopting new technologies in construction inspection.

The objective of this study is to summarize research efforts and practical applications of different types of visualization and Image modeling technologies used in transportation construction inspection. The current and future research trends are elicited from the collected articles. Further, practical information regarding what construction elements to be inspected by these technologies, effectiveness, and the enablers and barriers of technology adoption are also discussed.

2 Construction Inspection

Quality assurance (QA) inspection of construction project is defined as a tool or means by which the owner and contractors ensure that the road or bridge is constructed in accordance with approved plans and specifications by the most economical, efficient, and safe method [5]. When QA programs are well designed, they can provide confidence that project materials and workmanship will be in reasonable conformance with plans and specifications [6]. Typically, QA inspection and acceptance are managed by the means of material certification, visual inspection, or sampling and testing. While the acceptance by certificate is typically for standard and prefabricated materials with non-to-low inspection failure risk, the acceptance by testing and field inspection are often for project-produced materials and workmanship with higher levels of risk. To alleviate this risk, transportation agencies allocate resources to perform construction materials testing and inspect construction items as a part of their QA programs. Typically, inspection staff is responsible for conducting and verifying the results of the material testing and inspection processes. The inspection process may be on-site such as visual field inspection or off-site such as shop and source inspection [7].

Various indicators showed that the conventional inspection process has reached its limits, and numerous transportation agencies have begun shifting from the conventional testing and inspection to automated process aiming to save time, cost, and inspection workforce. These agencies are using a combination of manual and electronic systems and tools. The emerging e-inspection technologies such as visualization and image modeling enable easier access to real-time information and more accurate data collection. They also give inspectors access to a vast range of options that can help them complete inspection tasks in the field and documents inspection results [2, 8].

3 Research Approach

This study aims at identifying emerging areas, applications, and predictions of future research directions of visualization and image modeling technologies in transportation projects by conducting a systematic literature review on relevant articles published from 2000 to 2021. Transportation construction and maintenance related articles from construction, electrical and electronic engineering, and computer science journals domains were included in the review. As shown in Fig. 1, three

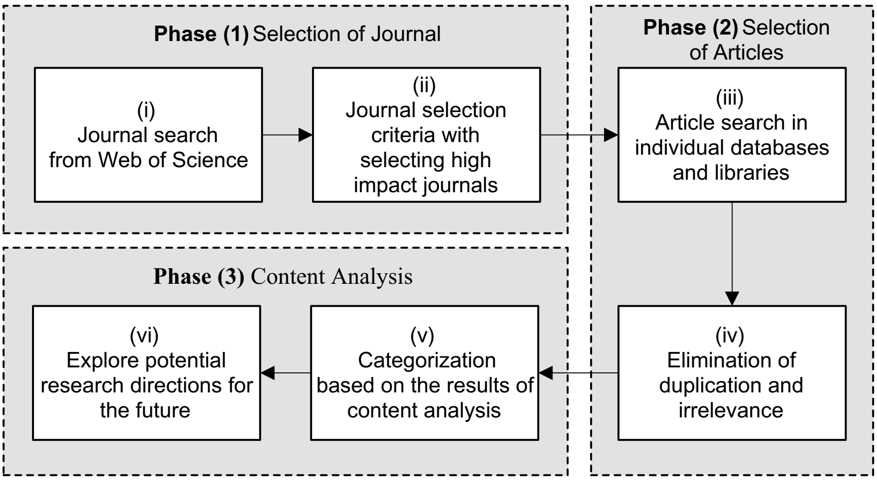


Fig. 1 Research methodology for acquiring up-to-date and high-quality articles

phases have been applied in this study to acquire up-to-date and high-quality articles. In Phase 1, journals that have an important impact and prominent position in the research community were selected. For a double authentication, two criteria have been assigned for journals selection, including a) the literature to be drawn from the top quality journals listed in the 2019 Scimago Journal & Country Rank (SJR) list, and b) the 2019 Scopus journal metrics (CiteScore) on the ranking of construction management journals were referred to when choosing the journals. Journals that have a CiteScore of 1.0 and above based on the 2019 Scopus journal metrics were considered [9]. In Phase 2, advanced search for relevant articles was conducted using Science Direct, Scopus (Elsevier's abstract and citation database), Google Scholar, and American Society of Civil Engineers (ASCE) library, Taylor and Francis Online, and Wiley Online Library. To consider publication from other fields pertained to construction inspection technology, Electrical and Electronics Engineers (IEEE) Xplore and Association of Computing Machinery (AMC) library databases were searched. A keyword search for "construction e-inspection", "highway inspection", "electronic construction inspection", "visualization technology", "image modeling "pavement testing" and "bridge testing", which are frequently used in transportation construction papers. In Phase 3, 93 searching results in the selected journals and databases from Phases 1 and 2 were analyzed (Table 1). By synthesizing articles' abstracts, highlights and key scope, 64 articles were outside the visualization and image modeling in construction project e-inspection domain. This screening process

Table 1 Number of articles pertaining to construction e-inspection of transportation projects

No	Journal			No. of article	
	Name	Cite-score	SJR	Total searching	Reviewed
1	Journal of construction engineering and management (JCEM)	5.8	1.03	11	4
2	Journal of computing in civil engineering (JCCE)	7.6	0.95	14	3
3	Journal of infrastructure systems (JIS)	3.4	0.64	7	2
4	Journal of management in Engineering (JME)	6.7	1.25	6	1
5	Automation in construction (AC)	9.5	1.41	22	10
6	Journal of structural engineering (JSTE)	5.7	1.64	5	1
7	Journal of surveying engineering (JSE)	3.9	0.88	4	1
8	Advanced engineering informatics (AEI)	6.9	0.94	5	2
9	Advances in engineering software (AES)	9.5	1.24	5	1
10	IEEE Instrumentation and measurement magazine (IEEE)	2.3	0.32	3	1
11	Journal of bridge engineering (JBE)	4.6	1.32	11	3
Total				93	29

reduced the number to 29 articles from 11 journals after duplicated and irrelevant articles were eliminated. In addition to these articles, six relevant academic reports were also selected for this research because they discuss these technologies.

Once the articles were identified, detailed content analysis was carried out. Content analysis is a research technique for determining major facets of and valid inferences from written, verbal, or visual communication messages [10]. Content analysis (i.e. paper title, abstract, keywords, methodologies, and technology demonstrations, or application areas) was conducted in order to categorize and analyze the reviewed articles.

4 Results

The result of the content analysis is presented in the following subsections. The percentage values indicated in the discussion, figures, and tables were determined based on the number of references over the total number of articles considered in the content analysis (i.e., 29 journal articles).

4.1 *Profile of the Reviewed Articles by Journal and Year of Publication*

Figure 2 depicts the percentage of the selected articles published in each journal. Approximately one third of the selected articles were published in AC, where the scope of this journal focuses on automation and technologies in construction. Approximately half of the articles were published in the journals of AC and JCEM combined. The remaining percentage of the articles (50%) were published in the other 9 journals. The number of selected articles by journal and year is shown in Fig. 3. The selected articles were published over the period from 2000 to 2021. Among these, 11 articles (38%) were published between the years 2015 and 2019, which is considerably greater than any other publication period. From 210 to 2014, there were nine articles (31%). From 2005 to 2009, there were five articles (17%). Whereas, the number of selected articles published in the span of 2000–2004 is four (13.7%), representing the least number of publications. As seen, the trend in Fig. 3 indicates an increasement in the number of publications and research in the area of visualization and image modeling technologies.

Table 2 a. Summary of multi-dimensional visualization technologies discussed in the selected articles

No	Technology	Description and application area	Related articles [percentage of related articles %]
1	2D vision tracker and sensor	Vision tracking technology used in construction projects for tracking site resources	[13, 14] [6.8%]
2	3-D scan and modeling	The 3-D model provides a virtual representation and visualization of project components. The data of the model can be used to automate construction activities, progress imaging and tracking, review plans, bridge inspection; falsework inspection, tracking construction equipment and materials	[11, 12, 15–24] [41.3%]
3	4-D scan and modeling	4-D model with progress imaging photographs is used in visualization of construction Progress and monitoring with 4D simulation	[25, 26] [6.8%]
4	Virtual reality (VR)	VR superimposes a computer-generated image and provides a composite view. It is used in comparing installed work with drawings and specifications and bridge modeling	[27, 28] [10.3%]
5	Augmented reality (AR)	Similar to VR, AR gives the user a view of the real world and. It is used in comparing installed work with drawings and specifications, bridge modeling, and inspector training	[27] [6.8%]
b. Summary of camera image-based technologies discussed in the selected articles			
No	Technology	Description and application area	Related articles [percentage of related articles %]
1	Video camera (VC) and image capture camera	VC is telepresence technology that has the capacity to stream high-quality video images of construction site to members of the project team who are not physically present at the jobsite. It is used in bridge inspection and monitoring construction progress	[29–33] [17.2%]

(continued)

Table 2 (continued)

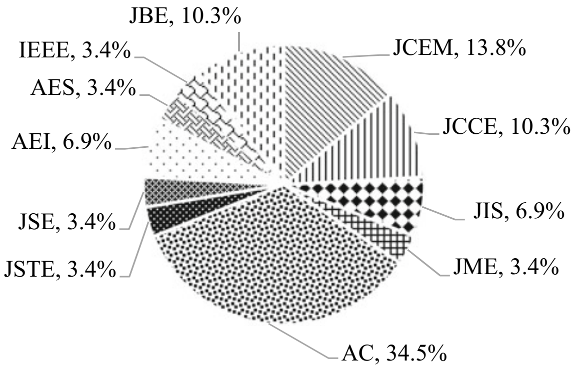
No	Technology	Description and application area	Related articles [percentage of related articles %]
2	Time delayed integration (TDI) camera	TDI is a scan system takes multiple pictures of the same line image and add them up to get an amplified image. It is automated cracking- survey system of pavement surface	[34] [3.4%]
3	High-resolution automated cameras (HRC)	HRC is a remotely operating technology that can provide construction management and other users with imaging feeds of job site activities such as tracking and updating project schedules	[35] [3.4%]
4	Thermal infrared (IR) imaging	IR is remote sensing technology used in assessing bridge deck and superstructure condition	[12] [3.4%]
5	Electro-optical (EO) satellite and airborne imagery	Airborne and remote sensing technology used in assessing condition of infrastructure such as bridges	[12] [3.4%]
6	Dual-light inspection (DLI)	DLI is used to categorize image. It consists of image capture, subtraction, enhancement, and classification. It is used in pavement surface surveying and distress detection	[36] [3.4%]
7	Mobile phone camera	HeadLight mobile technology system and application used in inspection of different construction elements	[4, 37] [6.8%]
c. Summary of other relevant technologies discussed in the selected articles			
No	Technology	Description and application area	Related articles [percentage of related articles %]
1	Photogrammetry	The photogrammetry is the practice of extracting precise geometric measurements from photographs. The photographs are typically acquired from airborne platform. It is used in bridge deck and superstructure photographing, progress measurement, and reporting of construction work	[11, 12] [6.8%]

(continued)

Table 2 (continued)

No	Technology	Description and application area	Related articles [percentage of related articles %]
2	Building information modeling (BIM)	BIM is the process of developing and using a computer-generated 3D/4D geometry model to link and analyze data related to the inspection, evaluation, and compare with the as-planned construction elements such as bridge components. Therefore, the planned state at any time can be derived and compared with the actual construction state	[38] [3.4%]

Fig. 2 Percentage of the selected articles published in each journal



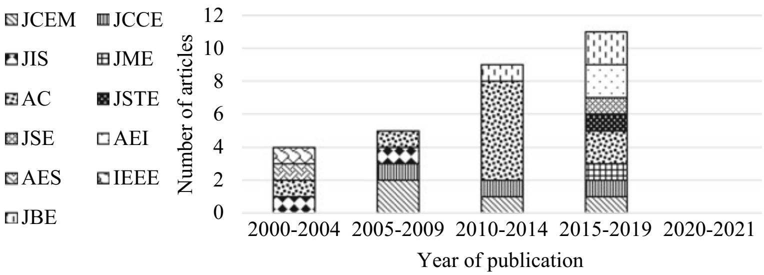


Fig. 3 Number of selected articles by journals and year

4.2 Summary of the Examined Technologies in the Reviewed Articles

One of the objectives of this study is to categorize inspection technologies and identifying the purpose of using each technology, the construction element was inspected by these technologies, and technologies were highly examined by researchers or required less attention. Table 2a–c shows the reviewed types of visualization and image modeling technologies as follows; multi-dimensional visualization technologies, camera image-based technologies, and other technologies such as Photogrammetry and BIM.

As shown in Table 2a–c, 14 construction technologies were used in visualizing and imaging inspection of different construction elements. These technologies may assist construction inspector to check construction progress and quantities, compare installed work with drawings and specifications, and track construction resources such as materials delivery. It can be seen in Table 2a that more than 40% of the reviewed articles have focused on 3-D scan and modeling technology, whereas technologies such as time delayed integration (TDI) camera, high-resolution automated cameras (HRC), dual-light inspection (DLI), thermal infrared (IR) imaging, electro-optical (EO) satellite and airborne imagery, and dual-light inspection (DLI) have less than 4% of the current research trend. Technology such as photogrammetry is a salient example of visualization tool. The photogrammetry extracts precise geometric measurements through photographing of objects, which is typically acquired from airborne platform. Examples of construction elements and activities inspected by the photogrammetry technology are bridge deck, progress tracking, and reporting of construction work [11, 12].

5 Discussion

Two areas of discussions have risen during result analysis, including: (1) current implementation and integration of visualization and image modeling technologies to achieve greater synergy and (2) future research directions.

The literature shows that emerging technologies have the potential to revolutionize the future of the construction industry through automated construction operations, and the visualization and image modeling lie among these technologies. Amalgamation of two or more of the e-inspection technologies showed a promising potential to overcome limitations of some of these technologies. For instance, 3D scanning was used to support progress measurement and project control. However, 3D scanning has limitations of the long time required to perform a single scan and the number of scan-positions necessary to acquire accurate information. To address these limitations, 3D scanning was integrated with photogrammetry. The result was enhanced speed and accuracy of data collection from construction site [11]. Another promising e-inspection area is connecting the visualization and image modeling technologies to project database via internet of things (IoT). Where, the IOT uses the internet connectivity to form a platform that is used to execute any specific function through the network. Connecting the visualization and image modeling devices with everyone in all times and locations of the project using the built-in wireless connection eases the monitoring and control process of project for inspectors [39]. The current trends suggest some possible directions for the future research in the area of integrating e-inspection technologies. In particular, the literature review revealed that some significant problems are still exist on how to transfer data and models from application or device to another [12, 21], which require more investigation.

Emerging technologies continue to evolve, and new technologies are becoming more accessible for a wide range of highway construction applications. Table 2a–c presented description and application of 14 different visualization and image modeling technologies used in construction inspection. This may help transportation agencies identify what and how to inspect by these technologies. Research trend of developing the visualization and image modeling technologies during the past two decades indicated that certain areas of research become more salient, while others require less attention. For instance, the highest focus of research effort is on the technologies of 3-D scan and modeling (>40 of the reviewed articles). In contrast, technologies such as HeadLight mobile application, EO, and DLI have had less attention from researchers (examined in one article or academic report). This can be explained that, compared to the 3-D modeling, these are recent-new technologies, still under evaluation, and have had limited deployment in transportation construction inspection [4, 40]. However, technology such as TDI is exist for more than a decade and still has less research development [34, 35]. In the future, researchers may need to explore why some possible technologies that are existed for a long time have not been applied widely. Additionally, practitioners may identify why these technologies have not been utilized more frequently in practice, and how to avail the construction industry better of the possible benefits of these technologies.

6 Conclusion

The three-phase research approach has been performed in this study to conduct content analysis of literature on the visualization and image modeling technologies used in construction inspection. First, construction engineering and management related journals that have an important CiteScore and SJR impacts were selected. Second, advanced search for e-inspection relevant articles between 2000 and 2021 in these journals has been conducted. Finally, by analyzing articles, the search resulted in 29 articles from 11 journals. Additionally, six academic reports were also reviewed.

The result of analyzing these articles showed increased number of publications and research effort in the area of visualization and image modeling during the last two decades. 14 technologies shown in Table 2a–c were employed in variant construction inspection and testing processes. The current research and application directions of merging two or more of the e-inspection technologies showed promising potentials to overcome limitations of some of these technologies. While some of the e-inspection technologies have proven their feasibility, there are a considerable number of other technologies are still under evaluation and have had limited deployment in highway construction inspection. Overall, although these technologies are still in an innovation or seed phase, it can be expected that with continued effort put into research and development, they may soon approach the growth phase and encounter adoption by transportation agencies on a larger scale.

This study suggests future research directions. For integration purpose, there is a need for approaches that transfer data between the different e-inspection technologies. Researchers and practitioners need to explore why some e-inspection technologies that existed for a long time have been utilized less frequently in practice. The findings of this study are of value to researchers and industry practitioners seeking a useful reference on adopting new technologies in highway construction inspection.

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A Market Accessibility Study of the Inland Waterway System in Mississippi

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1 Introduction

"Blue Economy", defined as "the sum of all economic activity having to do with oceans, seas, harbors, ports and coastal zones" [1], refers to a wide range of economic activity in the maritime sector. This definition drew from the work of Dr. Judith Kildow as published by the National Ocean Economics Program in The National Report: State of the U.S. Ocean and Coastal Economies, 2009. Given the unique geography of the state of Mississippi, it becomes a major competitor in terms of the "Blue Economy" related activities. An analysis conducted by professionals from The University of Southern Mississippi initiatively identified an entire Blue Economy system in the state and recommended strategies to reach its fullest potential [2]. In Mississippi, 25 million tons of goods has been moved through the Port of Gulfport every year. But the maritime economy extends far beyond the sea ports and ocean to include all waterborne and land systems, such as river ports, various transportation means on land, and port-dependent industries. To realize the potential of the entire Blue Economy system, river ports also need to be integrated and utilized with other freight systems so to maximize their competitiveness in maritime freight and Blue Economy.

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S. Walbridge et al. (eds.), *Proceedings of the Canadian Society of Civil Engineering Annual Conference 2021*, Lecture Notes in Civil Engineering 247,
https://doi.org/10.1007/978-981-19-0968-9_36

To address this need, the study aims to quantify the potential of each port to interact through trading with industries that rely on waterborne transportation. Goods movement through each port was summarized to track the changes in the traffic and more importantly identify the port-dependent industries. An intermodal network consisting of ports, railways, highways, and counties were developed to analyze the traffic movements and costs on different freight routes. This network is the first of its kind in the State of Mississippi. The intermodal network provides the necessary foundation for the state of Mississippi to model any future change to the freight system, either at nodes or on links. The accessibility assessment identifies ports with the highest potential in terms of their capability to serve port-dependent industries in the state. This assessment can also be used in the future to explore uncovered new markets and niche services for the ports.

2 Overview of Mississippi Port Traffic

According to Mississippi Department of Transportation [3], there are 16 public ports in Mississippi, including:

- Gulf Coast ports—Bienville, Gulfport, Biloxi, Pascagoula.
- Mississippi River ports—Rosedale, Greenville, Vicksburg, Claiborne County, Natchez.
- Tenn-Tom ports—Yellow Creek State Inland Port, Itawamba, Amory, Aberdeen, Clay County, Lowndes County.
- Yazoo River Port—Yazoo County.

One thing to be noted here is that the 16 ports of Mississippi are owned and operated by various entities. Yellow Creek State Inland Port and the Port of Gulfport are the two ports owned by the State of Mississippi. Other ports are publicly owned but sometimes operated by private companies. For example, the Port of Amory, Vicksburg, and Columbus are owned by the cities but operated by Watco Companies, LLC, which is a transportation company providing terminal and port services. The Clay County Port, also named as "Raymond D. Lucas Memorial Port", is owned by the county but managed by the local drayage companies. Another thing worth mentioning is that while all the ports are functioning as transportation terminal facilities for moving goods, the Port of Biloxi is mainly a recreational marina with piers, boat ramps, fishing bridges, and boat launches.

2.1 Waterborne Traffic Volumes

The freight statistics summarized here serves as an update of a study conducted by Cambridge Systematic, Inc. for MDOT [4]. In that study, data of 2011 drawn from the U.S. Army Corps of Engineers Waterborne Commerce of the United States was used to summarize the port traffic by direction, by port, and by commodity type. This study provided an update of the statistics using data from 2011 to 2017 from the same data source [5]. The volume of goods recorded in the waterborne database were measured by the unit of short ton. One short ton equals to 0.91 metric ton, and 0.89 long ton. In this study, short ton is used as the unit for all the waterborne traffic volumes and is short formed as ton.

A total of nearly 45.807 million short tons of freight was shipped through Mississippi ports in 2017, including shipments by water to, from, and within individual ports. This number reveals a 17% decrease from the 55.158 million short tons in 2011. Individual ports have various performances. The tonnage through Yazoo had a 57% increase compared to itself, followed by the Port of Natchez's 51% increase and Greenville's 16% increase. At the same time, a 65% decrease occurred to the Port of Biloxi, companied by a 30% loss at the Port of Pascagoula.

2.2 Types of Goods

A total of 45.807 million tons of freight shipped through Mississippi ports in 2017 consists of multiple types of goods, including manufactured equipment and machinery, chemicals and related products, coal, lignite and coal coke, crude materials, inedible except fuels, food and farm products, petroleum and petroleum products, and primary manufactured goods.

More than half of the total tonnage handled by the state's ports is petroleum and related products. These commodities accounted for almost 28 million tons in 2017. The next largest commodity group is chemicals and related products at just over 7.3 million tons, with almost the same share (both carries 14% of the total) as the group of food and farm products. A comparison of these breakouts between 2011 and 2017 reveals the trend of a greatly enlarged share of food and farm products and a slightly enlarged share of chemicals and related products at the expense of a shrunk share of petroleum and related products.

3 The Statewide Intermodal Network

3.1 Network Building Blocks

Transportation modes included in this study are limited to truck and rail shipping since the goal is to investigate the ports' accessibility to their markets on the land side instead of the waterway side. The resulting intermodal network is composed of two primary sub-networks, namely the highway network and the rail network in Mississippi. Since the goal of the study is to assess ports' accessibility to potential markets that depend on port-related shipments, it is natural to understand that the 16 ports of Mississippi will be used as origins for shipments. However, the selection of destinations requires more consideration. The way to identify those potential markets requires economic related data such as location quotients of industries, which will be discussed later. Thus, destinations need to be the places where the economic data can be collected successfully. The space unit for such data collection is county level, which means economic activity data will be collected and aggregated for each county. The geographic centroid point of each area shape of a county will be used as the approximate center for the economic activities within that specific county. As a result, 82 county centroids were included in the network model for further calculation.

The abovementioned single-mode networks, origins, and destinations, were connected by a set of intermodal transfer terminals or load centers where containers are off-loaded from one mode and loaded onto another. In this intermodal network model, a terminal facility is composed of gates and transfer links inside the terminal. A terminal gate represents the connection between a single-mode network and an internal transfer function. A terminal transfer link serves to represent the processes involved in the transfer of shipments from the original mode to the next mode, or vice versa, within a terminal. Connection between a single-mode network and a gate is represented by a bi-directional link egressing from or accessing to that transportation mode. For highways, access links represent local streets that serve as collectors for the arterials in the national highway network. For rail, access links represent industrial spurs not contained in the rail network. For waterways, access links represent the distance across a broad channel or harbor to a dock.

Collecting detail shipping cost information is a task that is clearly beyond the scope of this study. Instead, we adopt the approach implemented by CTA to estimate impedances for each link element of the intermodal network, namely single-mode network links, terminal transfer links, and egress/access links. The approach of impedance was also used by many previous studies [6–8]. CTA calibrated impedances for a generic commodity in such a way that the characteristics of flow distribution between origins and destinations recorded in the 1997 Commodity Flow Survey (CFS) are best reproduced. It should be stressed that the overall system of shipping impedances is designed to produce modal route selections in line with CFS freight survey data, rather than to estimate actual freight shipping costs.

Impedance of a transfer link capture all the processes and costs involved in the transfer of shipments within a terminal, for example, loading, unloading, break bulk, storage, drayage, etc. Impedance of a highway link derived from the mileage, speed, presence of a toll, truck route destination, and the urban/rural functional class of the corresponding link in the real-world shipping network. Impedance of a railway link is determined by the “main line class” and an evaluation of line importance, by annual traffic volumes [7]. Since the access links are defined as the subset of either the highway network or the railway network, their impedance values are defined in the same way as it is for the highway or railway links.

For each shipping model, the impedance value is normalized so that approximately one impedance unit corresponds to shipping one mile on a link under the best possible conditions for this mode. Highway impedances typically range from 0.9 times the link mileage for rural interstates, to 5 times the mileage for two-lane urban streets or unpaved rural roads. Rail impedances also vary between 1 time the mileage for A-mainlines to 4 times the mileage for the lowest traffic B-branch lines. Impedances on access links are 5 times the mileage of the link, including its 20% circuity. Waterway access impedance includes its straight-line distance. The impedance function for terminal links is in a simple look-up table based on the type of terminal.

3.2 Connecting the Building Blocks in ArcGIS

In ArcGIS, all the building blocks needed in establishing the intermodal network can be classified into two groups: links and nodes. In the intermodal network, highway and railway links are the physical facilities where movement of goods occur. Access links physically or logically connect ports, county centroids, and terminal gates to highways and railways. Transfer links serve as logical connections to move goods from one transportation mode to another within terminals. In such a way, all the node and link layers are connected to each other to establish the first-of-its-kind intermodal network. The Port of Gulfport intermodal network shows the intricacies of the access points as in Fig. 1.

3.3 Modeling the Goods Movement on the Intermodal Network

Two types of transportation modes are included in the study: moving goods from ports to markets by "truck only" and by "truck + train". Since the goal of the study is to assess the accessibility of ports to their potential markets, goods movements from ports to county centroids are the subjects of the freight modelling in the intermodal network. Thus, there are various types of movement chains modelled. For example, in the intermodal network, goods can be shipped from a port to a county by using the direct access link, by transferring from a barge to a truck and then moving through highways to a county, or by transferring from a barge to a train and then moving through railways to a county. If intermodalization is needed, the goods from a barge can be handled in the terminal and transshipped between trucks and freight trains as needed to reach the destination county.

Endless combinations of such movement chains can be generated from an origin to a destination. However, to calculate the accessibility index, only the route with the smallest impedance value will be recorded for further analysis. To find the "least impedance route", the built-in tool in ArcGIS called "Closest Facilities" was used and the total impedance for each "best route" was recorded for each origin–destination pair. Optimized routes found with the lowest impedances between ports and county centroids were charted in Fig. 2. The green lines show the routes with the lowest

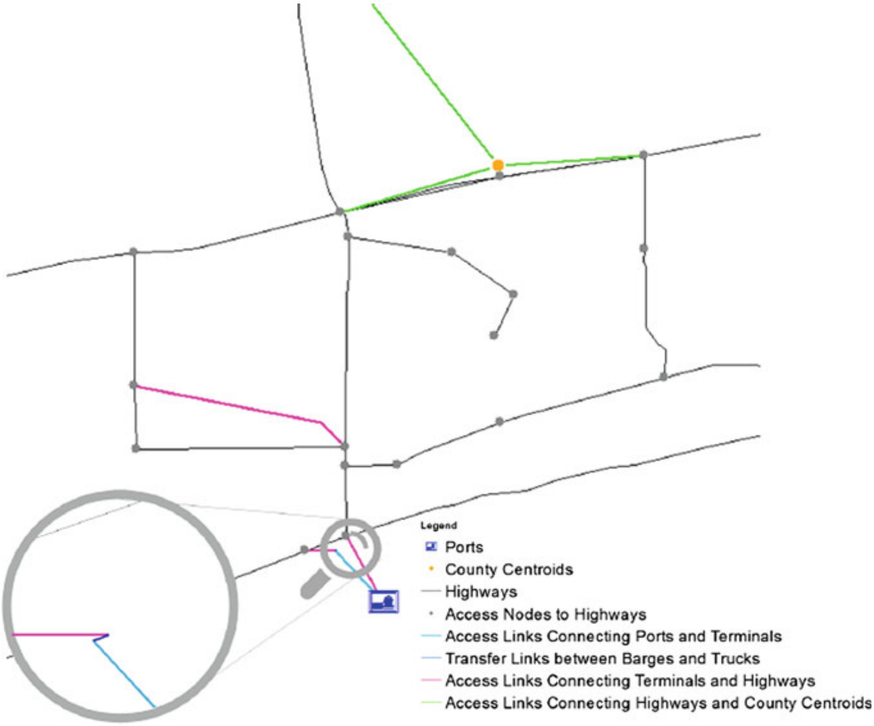

Fig. 1 Part of the intermodal network near the port of Gulfport

impedances between certain pairs of ports and county centroids using only highways, while the red lines are that of using highways and railways. It is found that most of the routes stay the same when switching from single mode network to intermodal network. The only difference occurs at the northeast corner of the network, where the ports on Tenn-Tom waterway seat. The impedance values of the routes will be used in the accessibility calculation in the next section.

4 Accessibility Assesment

A priority goal of any transportation system is to grant access to certain destinations. As a place-specific concept, accessibility relates to the ability to have interactions with other locales. Accessibility represents how easily spaced-out economic opportunities can be apprehended through trade from a reference location, using a particular transportation system [9]. Similar to an array of transportation modes that are physically distinct from one another, waterborne transportation also depends on effective connections and coordination among ports and other modes to be competitive and to provide value to shippers. The accessibility of a port could quantify its ability

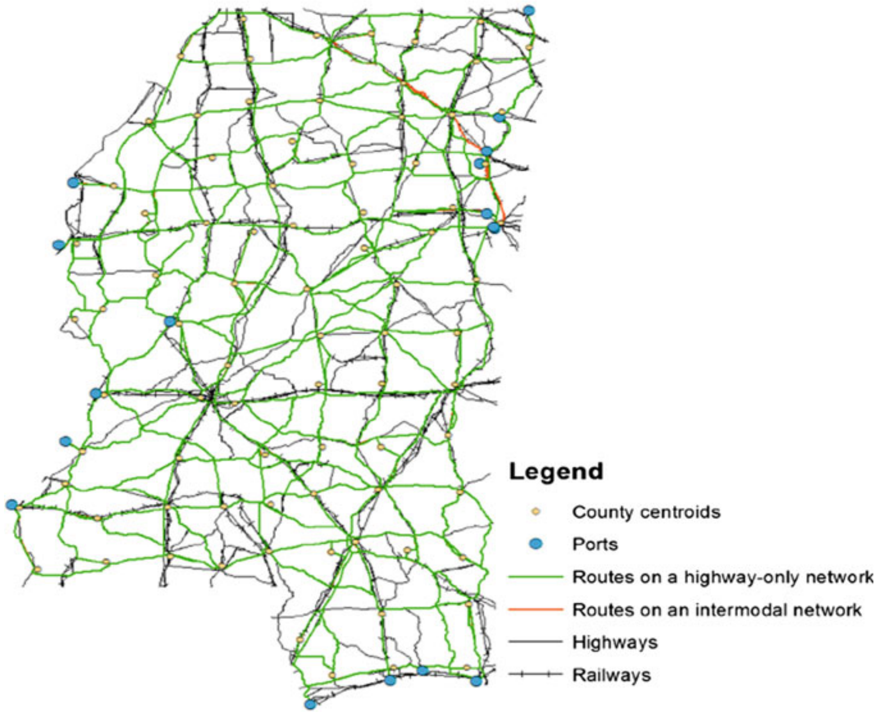

Fig. 2 Optimized routes between ports and county centroids

to apprehend port-dependent economic opportunities. A higher accessibility index implies higher potential for a port to be used in port-related shipments.

4.1 Accessibility Formula

A thorough review of accessibility measurements was conducted to determine the approach to use in this study. Location-based measures of integral accessibility associate proximity factors such as distance between origins and destinations with accessibility of a destination location. These measures represent the economic attractiveness of a location, taking into account the trade and interaction opportunities offered by other locations and the impedances to reach them in a transportation network [10, 11]. This is exactly what the study wants to assess for each port in Mississippi. In order to take into account the impeding impact of distance between two locations on the accessibility, a gravity-type potential accessibility measure was chosen, as represented by Eq. 1. The gravity-type measure assumes that two places will interact with each other in proportion to the product of their interaction activity level and inversely according to some function of the distance between them.

$$A_i = \sum_{j \in L} M_j f\left(C_{ij}; \beta\right) \tag{1}$$

In this equation, Ai is the measure of accessibility at port I; L is the set of all potential markets; Mj is the mass of economic opportunities available at potential market "j". f (cij;β) is the impedance function of shipping cost. Gravity style impedance function is chosen to quantify the relationship between impedance on a route and its attractiveness to a shipment; cij is the shipping cost from port i to market j by the multimodal or single modal network. It could be time cost or money cost. In this study, this cost will be estimated by impedance values from the Center for Transportation Analysis (CTA) at Oak Ridge National Lab (ORNL); β is the coefficient that represent how sensitive the impedance is to the change in shipping cost. In this study, three levels of β, 0.0030, 0.0023, and 0.0014, will be used to represent highly, medium, and low sensitive scenarios respectively. All the underscored key variables will be customized and discussed in the next section.

4.2 Accessibility Formula Customization

As shown in Eq. 1, the metric of place accessibility adopted in this study can be considered as a weighted average of the mass of economic opportunities available in all possible freight shipping destinations—counties, in the state of Mississippi. The identification of what should constitute the mass term can be problematic. Previous studies usually used population, gross regional product, or a surrogate measure of economic opportunity that is designed as a combination of a final demand (personal consumption expenditure) and intermediate demands (purchases) of manufactured goods, for the mass term. These may not be enough to represent the economic power that a place may have to generate containerized freight traffic that mainly depends on port transportation. Therefore, as shown in Eq. 2, we suggest using LQ index to represent the economic activity level of port-dependent industries at county level.

$$LQ_{ij} = \frac{E_{ij}/E_i}{E_{US,j}/E_{US}} \tag{2}$$

In this formula, Eij is County i's employment in port-dependent industry group j; Ei is Total employment in county i; EUS, j is total U.S. employment in port-dependent industry group j; EUS is total U.S. employment. Location Quotient (LQ) is a valuable way of quantifying how concentrated industry, cluster, occupation, or demographic group is in a region as compared to the nation. It can reveal what makes a particular region "unique" in comparison to the national average. Location quotient is ratio that compares a region to a larger reference region according to some characteristic or asset. Industry LQs are calculated by comparing the industry's share of regional employment with its share of national employment. Suppose that Breweries account for 0.16% of all regional jobs but only 0.015% of all national jobs. The regional

LQ for Breweries which then be (0.16/0.015) = 10.67, meaning that Breweries are nearly 11 times more concentrated in the region than average.

This study employs the industries identified in the port economic impact study funded by MDOT in 2014 as the target customers for port authorities [3]. According to the Cambridge study, Mississippi's top port-dependent industries are Petroleum and mining products, Chemical manufacturing, Agricultural production and support activities, Steel manufacturing, Shipbuilding, and Seafood product preparation and packaging. Based on these findings and the additional investigation of the industry supply chains, this study chose eight industries as the port-dependent industries for further analysis, including Crop Production, Animal Production and Aquaculture, Forestry and Logging, Mining (except Oil and Gas), Wood Product Manufacturing, Petroleum and Coal Products Manufacturing, Chemical Manufacturing, Transportation Equipment Manufacturing. One thing to be noted is that identifying industries who might purchase or sell the products handled by Mississippi ports is a complex work which deserve a whole separate study.

The LQs of the port-dependent industries were obtained from Economic Modeling Specialists International (EMSI), a widely used labor market analysis software. Industry NAICS codes that represent the port-dependent industries were entered into EMSI to query the corresponding LQ index in each county in Mississippi. These numbers were based on the employment data from 2013 to 2018. The outputs of the LQ query is a list of counties and the corresponding LQ values of the port-dependent industries in the counties.

The deterrent effect of the transportation cost on potential freight flows was modeled by the exponential function expressed as in Eq. 3.

$$f\left(C_{ij}\right) = \exp(-\beta C_{ij}) \tag{3}$$

The exponential function is particularly useful in handling the 'self-potential' problem which happens when i = j, $cij = 0$. Since exp(0) = 1, the case of $cij = 0$ is trivially handled by the exponential function and the entirety of trade opportunities are accounted for in the estimation of accessibility scores [12]. As discussed previously, in this study the shipping cost is represented by impedance values on each route.

Ideally, the shipping impedance decay parameter β, should be directly estimated based on the real relationship between the real regional freight flow data and the shipping impedance along different routes. However, this is beyond the scope of this study, which is to showcase the capability of using accessibility to quantify the potentiality of a port compared to other peers. Thus, three alternative values were assumed for β, each one being consistent with a hypothetical, though realistic, scenario. In the first scenario, shipping costs were assumed to weigh most heavily on freight-flow distribution between ports and county centroids, where the direct effect of economic opportunities—LQs, on flow attraction was discounted by 95% for a shipping impedance of 1000. The second scenario assumed a reduced response of freight flows to shipping impedance, with the effect of the economic opportunities discounted by 90% for an impedance of 1000. The third scenario assumed the weakest

Table 1 Accessibility indices for the 16 ports in Mississippi using highway-only network and intermodal network

Port name	Accessibility		
	By highway only	By intermodal network	Increase
Yazoo county port	14.68742156	14.68742156	0
Aberdeen	13.99885243	14.00544886	0.006596
Amory	12.9282955	12.93438747	0.006092
Natchez	12.92300215	12.92300215	0
Claiborne county	12.49721418	12.49721418	0
Rosedale	10.99040657	10.99040657	0
Lowndes	8.950558715	8.957035891	0.006477
Gulfport	4.657221595	4.657221595	0
Yellow Creek	4.094965045	4.094965045	0
Clay county	3.991234784	3.991234784	0
Itawamba	3.795813703	3.795813703	0
Bienville	3.424488916	3.424488916	0
Vicksburg	2.830791029	2.831122721	0.000332
Greenville	2.692794336	2.692794336	0
Biloxi	2.482679901	2.482679901	0
Pascagoula	2.370151127	2.370151127	0

impedance decay effect on freight flows, where the effect of the economic opportunities was discounted by 75% for an impedance of 1000. The resulting three parameters are 0.0030, 0.0023, and 0.0014, respectively, as suggested in a report published by the state of Indiana [13]. In this study, the second scenario with medium level decay parameter $\beta = 0.0023$ was used for the demonstration of the accessibility methodology, because domestic shipping is more in line with the assumptions of scenario 2 [6].

Gravity-type accessibility measures were first computed on the highway network and subsequently on the intermodal network described above. Measures derived on the basis of the national highway network were taken as the baseline against which the reality of intermodal goods movement by using highway and railway networks was compared. When accessibility is modeled on the intermodal network, the least-impedance shipping route from a given origin to a given destination is either an all-highway route or a combination of highway and rail segments, depending on the respective route impedances calculated by ArcGIS' Network Analyst tool. When modeled this way, intermodal accessibilities cannot be worse than highway accessibilities computed under the same model parameterization. Therefore, discrepancies between the highway and intermodal accessibilities can be imputed entirely to the benefit of intermodalization. Table 1 contains statistics on the accessibility measures computed at 16 ports for of the second scenario of the exponential impedance function which is discussed earlier.

According to Table 1, the accessibility indices exhibit large variations across the state, within a range of 2 to 15. The comparison between highway-only network and intermodal network proves that using intermodal network for goods shipment could increase the accessibility of a port. For example, the Port of Aberdeen, Amory, Lowndes, and Vicksburg all have an increase in their accessibility switching from single mode network to multi-mode network. However, this increase ranges from 0.01 to 0.07%, which means that adding railways to intermodalize the freight network has very limited benefit on the accessibility performance of the entire network. A port with a higher accessibility index implies that it has higher potential to be involved in port-related shipments. Yazoo County Port is well ahead of its peers and ranked No. 1 among the 16 ports, followed by Aberdeen, and Amory. Pascagoula is ranked the last position in this ranking, with Biloxi, and Greenville having very close accessibility values. Based on the accessibility indices, a map of the accessibility indices, shown in Fig. 3, is also provided to visually illustrate the distribution of the capability of ports to access their markets.

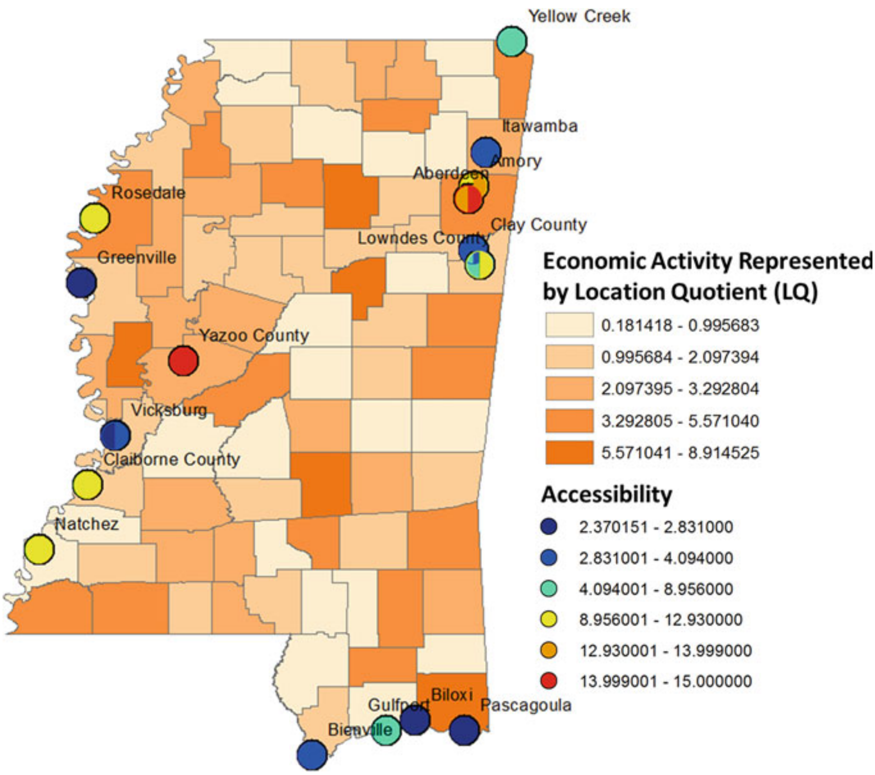

Fig. 3 Port accessibility distribution and change by using single mode and intermodal networks

5 Conclusions and Limitations

This study established a quantification method for market accessibility of each waterborne port in Mississippi, including both sea ports and river ports. An intermodal freight network has been established for the state of Mississippi. This network consists of physical facilities such as ports, highways, railways, terminals, and transfer/access links that connect all the physical facilities. This network is the first of its kind in the state and able to optimize shipping routes with regard to any type of cost. Based on this intermodal network, an accessibility quantification method was developed to transfer best practices of this concept into a river ports evaluation, with an adjustment to accommodate port related industry needs. Using this method, accessibility of each port to its potential markets was calculated using a single-mode network (highway only) and intermodal network (highway and railway). Although this study has some unique contributions, the authors also realize that there are limitations of this study and recommendations of future studies are summarized as follows.

5.1 Impedance Update

The impedance values used in this study was calculated by CTS based on its goal to reproduce the freight distribution patterns same as it was surveyed in 1997. Thus, the impedance does not directly relate to either the time cost or shipping fee involved in traversing each facility. In addition, this impedance values have not been updated since its first introduction. Network improvements after 2000, related to freight facilities and routes, were not reflected in the data source. Last but not least, the data source was established to represent the national network, which could neglect local routes and facilities. To address these issues, an updated impedance dataset containing accurate shipping cost in both time and monetary units should be developed in the next study to reflect recent and local efforts in improving freight transportation. Furthermore, the accessibility measures quantified here are based on current transportation network. So that the priority of a port's potential in shipping is of current-state. If planned transportation network changes can be reflected into the network data by updating the impedance values for each network link, then a future-state accessibility potential of a port can be estimated as well.

5.2 Expanded Potential Markets

The markets considered in the accessibility assessment are those locations within the state of Mississippi. However, regions on the border between Mississippi and its neighboring states, such as Alabama, Tennessee, Arkansas, and Louisiana should also be considered for more comprehensive results. Adding these expanded regions could increase the accessibilities of ports on the border of the state. It also can uncover new unknown markets and capabilities for specific port authorities.

5.3 Crosswalk from Port Handled Products to Port-Dependent Industries

The list of industries used in this study is only based on a similar study conducted by Cambridge Systematics, Inc and a preliminary study on industry sales and supply chains. A further study should be conducted to focus on the crosswalk between products and industries. The authors suggest to investigate all the industries related to each product type, including both downstream user industries and upstream producer industries. Product sales and industry supply chains should be repetitively compared and matched to select industries who might be using a certain product as its production material or who might be selling a certain product as its end product.

Acknowledgements The authors express appreciation to the following agencies and individuals who funded and contributed to the study. This study was prepared under contract with the Mississippi State University Institute for Systems Engineering Research ("ISER")/Center for Advanced Vehicular Systems—Extension (CAVS-E), with financial support from the U.S. Army Engineer Research and Development Center (ERDC).

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Construction of Rigid Pavement in Emerging Economies: Challenges and Opportunities

Anh D. Chau, Hiep T. Hoang, Long D. Nguyen, and Long Le-Hoai

1 Introduction

Infrastructure in general and transport infrastructure in particular are the physical foundation that plays a particularly critical role in the country's socio-economic development. An efficient transportation system helps promote production and business activities, reduce the transport costs, respond to the travel needs of the society, and connect economic regions. Vietnam is one of the emerging economies in Southeast Asia where the development of road transport infrastructure is significant for the country's development. In fact, the [3] indicated that Vietnam has spent around 5.7% of the Gross Domestic Product (GDP) every year in infrastructure which is the highest in the region. The question is how the country can effectively use and manage that large infrastructure budget to continue to maintain and leverage the growth of the emerging economy. Although the question pertains to multiple facets of infrastructure development, this paper focuses on the development of roadway construction. Addressing this question sufficiently is expected to provide the lessons from which other and similar economies may learn.

Although concrete structures have a long history in human history, it was only until 1865 that the first concrete pavement was constructed in Inverness, Scotland [1]. Since then, rigid pavement (i.e., concrete pavement) has continued to

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S. Walbridge et al. (eds.), *Proceedings of the Canadian Society of Civil Engineering Annual Conference 2021*, Lecture Notes in Civil Engineering 247,
https://doi.org/10.1007/978-981-19-0968-9_37

evolve and expand to most countries in the world, especially in developed countries (e.g., U.S., Canada, Germany, Austria, China, Australia) [18]. Nowadays, rigid pavement still receives much attention from academic scholars and professional managers. Conferences about rigid pavement research and development are often maintained annually. However, the use and expansion of rigid pavement is still relatively limited in emerging economies [19]. Although several studies have recently begun to examine the technical and structural aspects of rigid pavement application in Vietnam [9, 26], there is very little research exploring the management considerations on applying rigid pavement. Therefore, this study explored management considerations on applying rigid pavement using data from a survey instrument on opportunities and challenges of rigid pavement design and construction. Based on the result of the analysis, this paper discusses implications for enhancing the use of rigid pavement in Vietnam. The paper is to contribute to the limited but growing literature on the application of rigid pavement in emerging economies.

2 Literature Review

2.1 Road Pavement

The road pavement is a combination of subbase, base, paving geotextiles, and surface courses which supports and distributes the traffic load to the roadbed [13]. Since the road pavement is directly impacted by repeated traffic loading and natural factors such as sunshine, rain, humidity, and fluctuations in temperature, the cost of road pavement often accounts for the largest proportion of the road construction cost. In operation and maintenance, road pavement is also the component where money is mostly spent [27]. Therefore, the quality of the road pavement directly impacts the quality of uses, operation and maintenance costs, and safety of transportation. Generally, there are various types of road pavement such as flexible pavement (i.e., asphalt pavement), rigid pavement, composite pavement, semi-rigid pavement [8]. This paper focuses only on rigid pavement and uses flexible pavement as a baseline for comparison.

Flexible pavements use bituminous or asphalt materials which causes the pavement structure bends or defects overtime due to the traffic load [8]. Most of the runways in the world use flexible pavement due to the ease of construction compared to rigid pavement. Rigid pavement uses hydraulic cement concrete which is constructed on a granular base layer over the subgrade soil [31]. Compared to flexible pavement, rigid pavement is substantially harder due to the high modulus of elasticity of cement concrete. In several countries, rigid pavement is considered synonymous with "long life", which describes the high durability, long service lives (i.e., 25, 30 or more years), and little if any maintenance required [18]. Technically, rigid and flexible pavement have the main difference on the distribution of the traffic load. Due to the high stiffness, rigid pavement distributes load over a wider area which makes the rigid pavement have a higher durability, compared to the flexible pavement [31].

2.2 Rigid and Flexible Pavements

To emphasize the importance of rigid pavement, a literature review is conducted on the differences between rigid and flexible pavements. To provide a comprehensive comparison, the result is categorized based on the three sustainability pillars: environmental, economic and social [7]. Sustainability is one of the most important issues in the construction industry and academia. In fact, sustainable infrastructure is one of the first fundamental principles in the American Society of Civil Engineers Code of Ethics (i.e., “create safe, resilient, and sustainable infrastructure”) [2]. The Infrastructure Voluntary Evaluation Sustainability Tool (INVEST) developed by the U.S. Federal Highway Administration (FHWA) also aims at improving this sustainability triple bottom line [14]. In addition, the focus on sustainable construction and development is especially important for an emerging economy like Vietnam which is seeking for a reconciliation between economic and environmental development [25, 32]. Due to the limited space on this paper, we would like to focus only on several essential characteristics among the three sustainability pillars. The result of the literature review was summarized on Table 1.

In general, most studies supported the use of rigid pavement due to many benefits it provided. Zaabar and Chatti [34] study showed that trucks driven on flexible pavement consume around 4% more fuel than rigid pavement. In addition, since flexible pavement requires much more frequent maintenance and rehabilitation, excessive fuel can be wasted due to the traffic delays [5]. Rigid pavement also emits less carbon dioxide (CO_2) than flexible pavement during construction, maintenance, and operation. Batouli et al. [5] found that flexible pavement produced 61 times higher CO_2 compared to rigid pavement during the maintenance phase. On the other hand, flexible pavement tends to have a better recyclability than rigid pavement. Although [20] found that flexible pavement in the U.S. was recycled in larger quantities than rigid pavement, they also concerned the large uncertainty in the data that skewed their results.

A typical service life of rigid pavement is 25–30 years while flexible pavement is around 10–15 years [12, 20]. However, using these average numbers in service life estimation is not appropriate because the service life of any pavement is also impacted by various factors such as climates, materials, subgrade, and traffic. Nevertheless, rigid pavement is generally expected to have a long service life compared to flexible pavement [18]. A recent study showed that flexible pavements in the tropical region with overloaded vehicles lose their serviceability after five years and hence do not sustain for the longer design period [19]. The service life is one of the factors which directly influences the costs of the pavement. Although rigid pavement required a large initial investment, they often have lower life cycle costs due to the longer service life and low maintenance cost [5, 19, 30]. Nevertheless, the life cycle costs for rigid

Table 1 Rigid pavement and flexible pavement

Compared characteristics	Better performance	
	Rigid pavement	Flexible pavement
Environmental		
Lower fuel Consumption	[34]	
Global warming potential	[5]	
Recyclability		[20]
Economic		
Longer service life	[18, 30]	
Lower initial Investment		[16]
Lower life cycle costs	[5, 19, 30]	
Social		
Better nighttime Visibility	[23, 29]	
Quiet ride		[6]
Safety in Construction	[20]	
Less congestion	[18]	

and flexible pavement might largely vary depending on the construction locations (e.g., different climates and countries).

For the social dimension, rigid pavement appears to have a better visibility at night. Smith and Jolly [29] discussed that rigid pavement reflects light in a diffuse manner while flexible pavement reflects light in a slightly spectral manner. On the other hand, flexible pavement appears to generate less noise than rigid pavement [6]. For safety, flexible pavement produces a large amount of asphalt fumes which is highly hazardous for workers in construction [20]. Occupational exposure to asphalt fumes was found to have association with early liver and kidney dysfunction as well as hematological disorders [24]. As requiring less frequent maintenance and rehabilitation, rigid pavement can improve the traffic safety and reduce congestion [18]. In general, most studies agreed the use of rigid pavement better supports the three sustainability pillars than flexible pavement.

2.3 Need for Rigid Pavement in Vietnam

Vietnam has been considered as one of the emerging and dynamic economies, especially in Southeast Asia [4]. To maintain and enhance economic development, Vietnam has paid great attention to investment in the road transport infrastructure.

Road transport has served around 75.16% of all freight transport and 92.08% of all passenger transported in Vietnam [33]. Therefore, the development of road transport infrastructure is one of the most important goals of the Vietnam Ministry of Transport toward 2030 [33].

As a country that produces and exports a large volume of cement each year, Vietnam has the potential to develop and apply rigid pavement structures, especially to expressway projects. Since 2012, under the direction of the Prime Minister, the Ministry of Construction and the Ministry of Transport had a signing ceremony to increase the use of cement in the construction of transport infrastructure which aims to prioritize the use of domestically produced products (e.g., cement), promoting production and business, curbing trade deficit, saving energy and ensuring environmental hygiene. However, rigid pavement currently is only applied to projects on rural roads, some national highways and at some toll stations on the expressways. A statistic from the [33] indicated that rigid pavement makes up only 2.67% (i.e., mostly rural roads) of the total paved roads in Vietnam while flexible pavement accounts for 94.67% (e.g., expressways, national roads). To unblock this bottleneck, there is a pressing need in understanding the opportunities and challenges in applying rigid pavement. Therefore, this study takes a nuanced approach to explore the opportunities and challenges on the design and construction of rigid pavement.

3 Method and Analysis

To examine the opportunities and challenges of applying rigid pavement, we conducted a literature review on previous studies. The initial survey instrument was developed based on the result of the literature review. The instrument was then improved via interviewing and consulting with professional experts who had extensive experience on transportation design and construction (i.e., including the rigid pavement). Through the instrument development, 11 opportunity and 15 challenge items were identified for applying rigid pavement in an emerging economy (e.g., Vietnam). The final survey instrument was administered to another group of professional experts in Vietnam via the Google Form which is an online survey software. This study uses a sample of 42 completed responses collected from the survey. The demographic information of the sample was shown in Table 2.

In the survey, we asked participants for the level of agreement at each opportunities and challenges of applying rigid pavement using the 5-point Likert Scale: (1) Strongly Disagree, (2) Disagree, (3) Neither Agree nor Disagree, (4) Agree, (5) Strongly Agree. Means and standard deviations for each item were computed. The result was disaggregated based on the role that participants have held in the transportation projects (i.e., general contractor, consultant, and owner). This study used the partially overlapping samples approach where the sample included some participants experienced more than one role (i.e., there are small overlapping counts on General Contractors, Consultant and Owner) [21]. Percentages of overlapping observations within each subset are: General Contractor (35%), Consultant (59%), Owner

Table 2 Demographic of the study sample

Characteristics	N	%
Year of experience		
0–5 years	7	17
6–10 years	6	14
11–15 years	13	31
above 15 years	16	38
Highest position held		
Senior manager	5	12
Project manager	6	14
Head of department	14	33
Consultant	2	5
Engineer	15	36
Role in projects (some respondents experienced in multiple roles)		
General contractor	17	40
Consultant	34	81
Owner	9	21

(56%). Although the common practice in quantitative studies is discarding paired observations (respondents had overlapped roles), [10] discussed that the disposal of observations might cause bias and substantially impact the statistical power when sample sizes are small and/or the quantity of discarded observations are large. This is especially more important where participants experienced overlapped roles in this study are the one having the most experience in transportation design and construction. Therefore, the removal of these participants can create bias in the result. Derrick et al. [10] study showed that some simple statistical approaches (e.g., t-tests) can still be computed for the overlapping samples where assumption of normality has not been grossly violated. In addition, this paper focuses on providing a simple generalization using descriptive statistics rather than seeking for any statistical significance, so the use of partially overlapping samples approach is justifiable.

4 Result and Discussion

4.1 Opportunities of Applying Rigid Pavement

Table 3 showed the levels of agreement of participants at each opportunity item. In total, item O2 (i.e., uses cement which is available from various production plants distributed across the country) had the highest mean among the 11 opportunities. Owners and investors also had the highest mean on O2. In fact, Vietnam recently

Table 3 Opportunities of applying rigid pavement

Item	Mean (Standard Deviation)*			
	Contractor	Consultant	Owner	Total
O1. Has higher durability and longer service life	**4.18 (0.81)**	**4.45 (0.80)**	4.00 (0.71)	4.21 (0.84)
O2. Uses cement which is available from various production plants distributed across the country	4.12 (0.86)	4.32 (0.95)	**4.22 (0.97)**	**4.33 (0.79)**
O3. Withstands the hot, humid, and rainy weather	3.88 (0.70)	4.23 (0.75)	3.78 (0.97)	4.02 (0.84)
O4. Is capable to withstand high loads and its bearing capacity increases overtime	4.13 (0.62)	4.05 (0.79)	3.67 (1.12)	4.05 (0.86)
O5. Current construction technology meets requirements of rigid pavement	3.53 (1.07)	3.23 (1.07)	3.44 (0.88)	3.50 (1.02)
O6. Low maintenance costs during operation	4.13 (0.81)	4.05 (0.90)	3.44 (0.88)	3.93 (0.85)
O7. Consumes less energy during construction and operation	3.38 (0.96)	3.57 (0.98)	3.33 (0.71)	3.54 (0.91)
O8. Less rutting, and better visibility at night	**4.18 (0.53)**	4.36 (0.58)	3.56 (0.88)	4.17 (0.73)
O9. The government management agency plans to deploy pilot construction to promote the rigid pavement	3.13 (0.99)	3.36 (1.14)	3.00 (0.71)	3.33 (1.03)
O10. Can be recycled to form new aggregates in the composition of cement or in the road foundation	<u>3.07 (0.83)</u>	<u>2.91 (0.87)</u>	<u>2.67 (0.87)</u>	<u>3.03 (0.88)</u>
O11. We can learn from neighbouring countries using rigid pavement	**4.18 (0.73)**	3.95 (0.92)	3.56 (0.88)	4.02 (0.76)

*Within each column, the highest mean was bold, and the lowest mean was underlined

became the world leader in exporting cement and clinker in 2018, with nearly 32 million tons of exported products which is worth $1.2 billion. In 2019, Vietnam also exported 33.8 million tons of cement and clinker which reached the record levels of cement exported in the world [28]. In addition, there are many cement plants distributed nationwide which facilitate the reduction of the cost of transporting construction materials.

For the group of general contractors, they had the highest mean on O1 item (i.e., has higher durability and longer service life), O8 item (i.e., less rutting, and better observation at night), and O11 item (i.e., we can learn from neighbouring countries using rigid pavement). Most consultants also agreed on the O1 item. As the paper discussed above, previous studies also suggested that rigid pavement has a longer service life and provides a better visibility at night which can help save lighting energy [18, 23]. In addition, general contractors also looked for opportunities of learning from neighboring countries (e.g., other countries in the South, East and Southeast Asia).

On the other hand, O10 item (i.e., "can be recycled to form new aggregates in the composition of cement or in the road foundation") had the lowest mean among the groups of participants. Although there are few studies which discuss the opportunity of recycling the aggregates in rigid pavement [22], most participants do not think that it is an opportunity of using rigid pavement. Besides, O5 item (i.e., current construction technology meets requirements of rigid pavement), O7 item (i.e., consumes less energy during construction and operation.) and O9 item (i.e., the government management agency plans to deploy pilot construction to promote the rigid pavement) also had a mean less than 4.00 (i.e., agree). This result indicated that most participants were not confident that the current construction technology in the country was capable of meeting requirements of rigid pavement. In addition, they still have not perceived the opportunities of saving energy during construction and operation. Although there are calls from the government for applying rigid pavement, most participants do not perceive O9 item as an opportunity. This result indicated that the government and professional societies need to improve the communication and provide more support for the application of rigid pavement.

4.2 Challenges on Applying Rigid Pavement

Table 4 showed the level of agreement of participants at each challenge item. Most participants agreed that C5 item (i.e., has not piloted the rigid pavement to compare, learn from experience, widely implement in the future) is the most challenging for government management agencies. Consultants and owners also had the highest score on C5 item. In project management, pilot projects are necessarily required for exploring and deploying new innovations and concepts. This is especially important for the consultants and owners to determine opportunity viability. The pilot project will allow the consultants and owners gain necessary knowledge before executing the project on a larger scale [35]. Although participants demanded a pilot project of rigid pavement, they did not quite agree on the C1 item which suggested that the government has no experience on applying rigid pavement. In fact, rigid pavement has been applied in several road sections near the toll booths on expressways, so the government still has some experience on rigid pavement. However, what consultants and owners might seek for is a comprehensive pilot rigid pavement project where knowledge and lesson learned databases are systematically updated to inform effective decision making in the full-scale implementation.

For general contractors, having the government providing large initial investment costs was most important to them (i.e., C3 item). Indeed, the financial difficulty of owners is one of the top causes of large construction project delays and cost overruns in Vietnam [17]. Therefore, the government needs to focus on improving the mobilization funding, especially at the beginning of the rigid pavement project. On the other hand, contractors did not think the challenges rely on issuing technical standards for rigid pavement (i.e., C4 item). As shown on Table 4, contractors believed in the opportunity to adopt these technical standards from other countries.

Table 4 Challenges on applying rigid pavement

Item	Mean (Standard Deviation)*			
	Contractor	Consultant	Owner	Total
The government management agency				
C1. Has no experience on applying rigid pavement	3.47 (0.94)	3.18 (0.85)	2.67 (1.00)	3.21 (1.00)
C2. Is afraid to change and approach new technology while prioritizing traditional construction technology	3.50 (0.97)	3.43 (0.98)	3.22 (0.83)	3.46 (0.90)
C3. Has difficulty in providing a large initial investment cost for applying rigid pavement	**4.00 (1.17)**	3.95 (1.00)	3.89 (0.93)	4.00 (0.94)
C4. Has not yet fully issued technical standards to design, construct, supervise, and accept for transportation projects applying rigid pavement	3.33 (1.05)	3.36 (1.18)	2.89 (0.93)	3.35 (1.14)
C5. Has not piloted the rigid pavement to compare, learn from experience, and widely implement in the future	3.81 (0.83)	**4.09 (0.97)**	**4.00 (0.00)**	**4.08 (0.76)**
At the front end planning				
C6. Consultants lack experience in evaluating and implementing rigid pavement projects	3.12 (1.05)	3.00 (1.15)	3.00 (1.12)	3.14 (1.05)
C7. The unified investment capital for traffic road projects has not been established which causes difficulties in evaluating and approving projects, especially with large initial investment capital	**3.81 (1.05)**	3.45 (1.01)	3.44 (1.01)	3.54 (0.98)
C8. Owners and consultants often ignore sustainable development criteria such as saving fuel, reducing urban heat effects, reducing lighting requirements	3.53 (1.36)	**3.86 (1.06)**	**3.50 (0.93)**	**3.72 (1.02)**
For construction				
C9. Owners lack experience in rigid pavement	3.00 (1.03)	3.14 (1.04)	3.00 (1.00)	3.12 (0.98)
C10. There are few contractors with sufficient capacity and experience in rigid pavement	**3.88 (1.11)**	**3.59 (1.10)**	2.89 (1.17)	**3.62 (1.08)**
C11. Rigid pavement requires modern and integrated equipment	3.59 (0.71)	3.55 (1.06)	**3.44 (1.01)**	**3.62 (0.85)**
C12. Rigid pavement is not suitable for construction in areas with soft soils	3.63 (1.02)	3.32 (1.43)	3.11 (1.36)	3.39 (1.28)
For maintenance and operation				
C13. Curing is required for rigid pavement, so it is only suitable for new construction traffic	3.29 (0.92)	3.05 (0.84)	2.89 (0.78)	3.17 (0.91)

(continued)

Table 4 (continued)

Item	Mean (Standard Deviation)*			
	Contractor	Consultant	Owner	Total
C14. Rigid pavement has joints. If the construction process is not guaranteed, it will affect the riding comfort	**4.47 (0.62)**	**4.27 (0.88)**	**4.00 (1.32)**	**4.24 (0.96)**
C15. Repairing rigid pavement defects is time consuming, costly and technically complex	4.06 (0.66)	3.91 (1.11)	**4.00 (0.00)**	3.95 (0.96)

*Within each column, the highest mean was bold, and the lowest mean was underlined

At the front-end planning, owners and consultants were more concerned about the ignorance of sustainable development criteria such as saving fuel, reducing urban heat effects, and reducing lighting requirements (i.e., C8 item). In fact, reconciliation between economic and sustainability development is still a major challenge for developing countries. To improve the sustainability development, [32] suggested that the government needs to improve the involvement with all related stakeholders in the project. It is important to raise the public awareness on the importance of sustainability development along with providing economic and legal incentives for sustainable projects. For the contractors, they had more concern on the unified investment capital on the early of the project (i.e., item C7). All contractors, consultants and owners had less agreement that consultants lack experience in evaluating and implementing rigid pavement projects as a challenge (i.e., item C6).

For the construction process, contractors and consultants were concerned about the small number of contractors with sufficient capacity and experience in rigid pavement (i.e., item C10) while owners had more concern on the needs of modern equipment (i.e., item C11). Dinh and Nguyen [11] previously discussed that the lack of heavy equipment and machinery has highly impacted the productivity of labor construction in Vietnam. In addition, the lack of integrated equipment might impact the quality of the rigid pavement. For maintenance and operation, all participants had the highest concern on the comfort of riding on rigid pavement if the proper quality control was not established in the construction processes (i.e., item C14). The quality of curling and warping of rigid pavement can impact the ride quality. FHWA [15] suggested that using fewer joints (i.e., longer panels) might be considered to improve the ride quality and the life cycle cost of the rigid pavement. On the other hand, all participants are less concerned that rigid pavement is only suitable for new construction traffic (i.e., item C13).

5 Conclusion

The paper has provided an overview on the opportunities and challenges of applying rigid pavement in the emerging economies. Through the survey results, rigid pavement has been found to be highly potential for application in Vietnam. Promoting the use of rigid pavement is going to be a trend of many emerging economies in the world. Still, there are some challenges ahead which require more attention, support, and collaboration among the project stakeholders (e.g., government, construction companies). Government (i.e., project owners) need to actively look for strategies to attract more infrastructure funding (e.g., private sector); therefore, they can allocate on the large initial spending on rigid pavement and guarantee the stable disbursement throughout the construction. The [3] estimated that Vietnam currently requires around $480 billion on infrastructure development until 2030, however, the government can only afford one third of that need. The other two third need to be supported by private sectors. Construction companies (i.e., general contractors and consultants) should continue to adapt new construction technology and provide necessary training for employees in rigid pavement. In addition, more research should be conducted on rigid pavement to identify drawbacks and recommend innovative and effective solutions. For emerging economies, one of the pressing needs is to accurately determine the life cycle cost and construction time associated with rigid pavement projects. Currently, that information is very important for making investment decisions on rigid pavement. It can provide the country a long-term vision on using and managing the state budget. Future research should study the life cycle costs of rigid pavement and evaluate actionable strategies for applying rigid pavement in emerging economies.

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Developing a Gis-Based Fleet Optimization Model for Winter Maintenance Operations

P. Nguyen and D. Tran

1 Introduction

Management of winter maintenance operations is a complex process and critical to provide safe travel routes for the traveling public that requires the United States' departments of transportations (DOTs) to spend substantial resources on snow and ice control activities and operations [3]. For instance, the Kansas departments of transportation (KDOT) spends from $7 million to $22 million annually on their maintenance activities to operate multiple fleets of snow-plow trucks during winter months [8]. The deployment of such a large number of trucks over a vast maintenance area creates an operational problem in determining the optimal maintenance routes and fleet size while satisfying the LOS requirements for snow and ice route removal operations. Several DOTs have attempted to streamline their snow and removal process using a variety of methods, including heuristic approaches, mathematical models, and off-the-shelf software packages [6, 10]. For example, Ohio DOT employed a route optimization program based on the geographic information system (GIS) to model snow and ice routes within three of their ten Districts [11] to optimize their fleet size and determine if new truck facilities needed to improve the level of service (LOS) for winter operations. Results from recent studies [1, 9] that incorporated modern technologies (e.g., GIS) and modeling techniques (optimization algorithms) in collecting and analyzing spatial and geographic data show an increase in efficiency and a reduction in the number of trucks needed to accomplish their snow removal operations. This study aimed at developing a snow-plow fleet optimization model for KDOT's winter maintenance operations in District 4, one of six Districts within the

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S. Walbridge et al. (eds.), *Proceedings of the Canadian Society of Civil Engineering Annual Conference 2021*, Lecture Notes in Civil Engineering 247,
https://doi.org/10.1007/978-981-19-0968-9_38

State of Kansas. It is expected that the result of this study can apply to other Districts after successfully conducting a pilot study in the selected District 4.

2 Literature Review

A literature review was conducted to investigate the current state of practices in developing and implementing snow-plow optimization models for winter maintenance operations in North America within the past decade (2011–2021). The emphasis was placed on the development process of snow-plow optimization models, utilized tools (e.g., GIS-based software packages), and the evaluation and assessment process related to the anticipated winter operations budget. Relevant technical articles and white papers were also reviewed to better understand how optimization models were developed and implemented. From a pool of collected documents, this study selected eight academically published articles regarding the optimization of snow and ice routes and fleet sizes using innovative algorithms and GIS-based technologies for reviewing in detail. A summary of the selected articles is shown in Table 1.

3 Research Objectives

Current practices of winter maintenance on snow and ice route removal winter operations in the U.S and Canada show an urgent need regarding the use of advanced route optimization models to improve snow removal efficiency in winter operation activities. The major goal of this study was to develop a snow-plow fleet optimization model for all snow and ice routes within District 4, Kansas, USA, to enhance the efficiency of snow removal operations with time and cost savings while maintaining the safety and reliability of the roadways. To achieve the research goal, this study was designed with three objectives: (1) digitize all snow and ice base routes along with available truck facilities across the selected District; (2) determine the optimized routes and fleet size for the current snow and ice route removal operations; and (3) determine the total number of operational trucks needed for the selected District to maintain the current LOS requirements.

4 Methodology

The methodology of this study includes four steps: (1) literature review, (2) data collection, (3) fleet optimization model development, and (4) results as shown in Fig. 1. First, a literature review was conducted to summarize current practices in winter maintenance of snow and ice route removal operations. Second, geospatial data related to geography, route networks, LOS requirements, and recent snow and

Table 1 Summary of snow-plow optimization approaches for winter operation practices

Reference	Project goals	Optimization approach	Results
[2]	Design winter maintenance truck routes for single and multiple depots under the responsibility maps in District 3, Iowa, USA	Used a memetic algorithm to solve capacitated arc routing problems with constraints of cycle times, fleet size, truck capacities, and work duration	Reduced 13.2% of deadhead distance compared to current practices
[8]	Solve vehicle routing and scheduling problems of snow and ice removal practices for three counties in Delaware, USA	Developed a GIS-based optimization model for snow-plow routing to reduce the total travel distance and travel times	Reduced the total cycle times for completing each snow-plow route and provided different scenarios in performing snow and ice control activities
[1]	Identify strategies to enhance snow and ice removal operations for four counties within two Districts in Kentucky, USA	Utilized ArcGIS software packages with the Network Analyst extension and Vehicle Routing Problem toolset to investigate the performance of the current snow-plow routing practices	Minimized the operational trucks required to treat all snow and ice routes. Potential cost savings could reach $225,000 USD per year
[10]	Optimize snow-plow routes and fleet size for three Districts in Ohio, USA, by removing county borders	Developed a GIS-based snow and ice route optimization model using the ArcGIS software package and its extensions	Achieved total travel time savings of 837 min per treating cycle. Recommended adding thirteen more plow trucks to two Districts to maximize their level of service
[5]	Establish a base-map of winter highway treatment routes to improve service levels, optimize resource reallocation, and monitor changes to overriding constraints in region 4, Colorado, USA	Developed a snow-plow route optimization procedure with what-if scenario modeling	Optimized the fleet size in snow-plow operations, replaced old fleets, and recommended the use of mobile weather monitoring
[9]	Solve the vehicle routing problems of snow-plow operations in the City of Edmonton, Canada, to reduce the total operational costs	Used two integer programming capacitated arc routing problem formulations to minimize the total travel distance	Determined optimal depot locations to reduce total travel cost and required service time for snow plowing
[3]	Improve service efficiency while minimizing labor hours and fuel for winter maintenance operations in Vermont, USA	Developed a specific snow-route base-map to optimize the service areas for each truck garage based on the total travel time and the surrounding roadways	Efficient vehicle allocations based on the detailed roadways allowed the agency to optimize man hours and reduce fuel consumption

(continued)

Table 1 (continued)

Reference	Project goals	Optimization approach	Results
[6]	Enhance the level of service of winter maintenance operations by optimizing snow and ice routes and fleet allocations in Missouri, USA	Developed an integrated heuristic-based optimization algorithm for state transportation agency to identify the most efficient route plans and determine sufficient fleet allocations	Determine specific service routes that trucks can follow and optimal truck allocation scenarios with minimum cycle times and deadheading miles

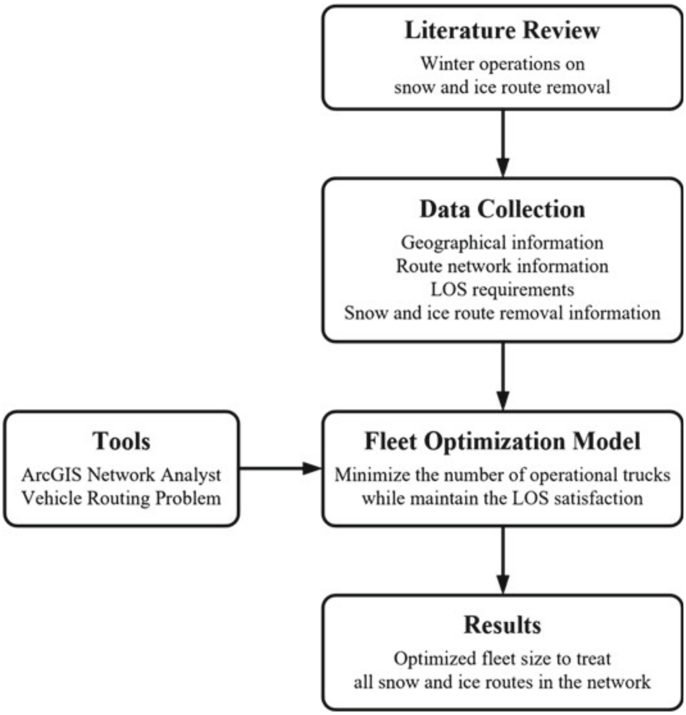


Fig. 1 Research methodology

ice route removal practices were collected. Third, a snow-plow fleet optimization model was developed for determining the minimum number of operational trucks needed at truck facilities to treat all required snow and ice routes while maintaining the current LOS satisfaction percent in District 4. Finally, optimized fleet size for all snow and ice routes in District 4, Kansas, was determined along with potential time and cost savings.

4.1 Data Collection

District 4, one of six Districts across Kansas, USA, as shown in Fig. 2, is responsible for construction and maintenance activities for seventeen counties in southeast Kansas. These responsibilities include providing snow and ice removal on the 3958 miles of state highways divided into sixteen sub-areas with different numbers of operational trucks located at each sub-area's truck facility that are housed in this District.

Several meetings with the KDOT executive management board to review and collect relevant snow and ice route information that they are responsible for in their winter maintenance operations. The route information data were collected in terms of printed maps with hand drawn routes and digital maps created by using spatial GIS-software. Specifically, the collected data include (1) geographical information (e.g., number of counties, county border limits, and terrain types across the selected district); (2) route network information (e.g., annual average daily traffic flow maps, highway length, roads hierarchy, travel directions, road distance, start and end points of each road in the network, turning locations/turn-around, and turning restrictions); (3) LOS information (e.g., number of lanes at each road in the network, snow and ice route priorities for maintenance, and typical salt application rates for each treating trip); and (4) snow and ice route removal information (e.g., number of snow and ice routes across the selected district, lane miles treated of each route, current fleet size, locations of truck facilities, and salt capacities at each facility).

District 4 is responsible for a total of 143 snow and ice routes in its winter maintenance network as shown in Fig. 3 and consists of seventeen truck facilities (or truck inventory) associated with their remote sites (or refill stations) within its seventeen counties. The current KDOT snow removal plan divides roadways to be treated during snow events into three categories based on the targeted LOS [7]: (a) Priority

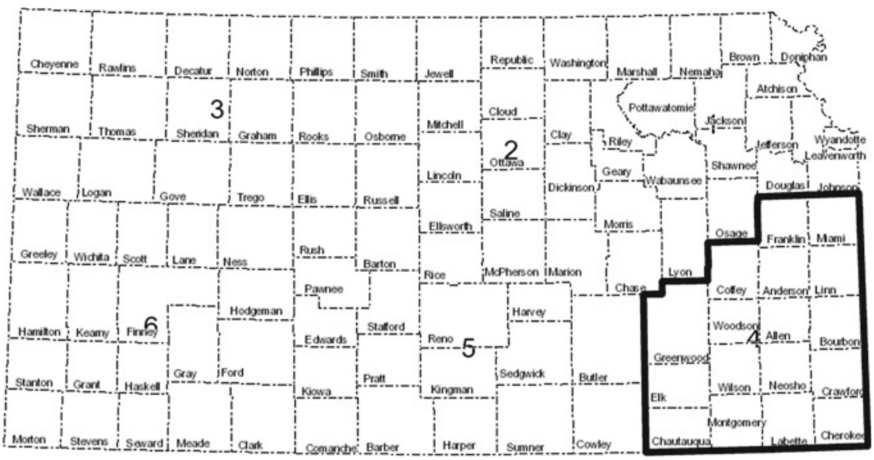
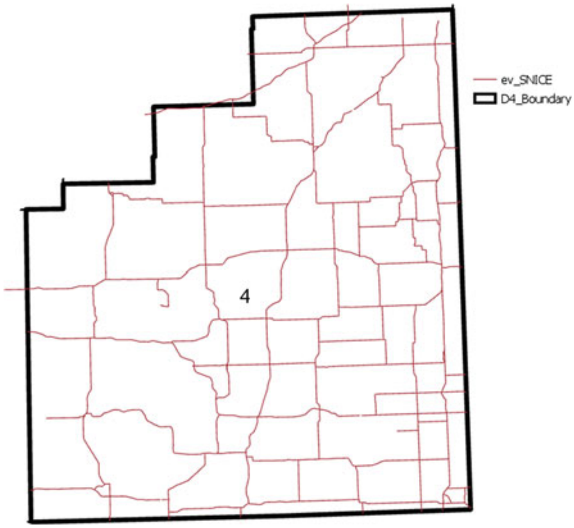


Fig. 2 Selected District 4 and its counties for implementing the fleet optimization model

Fig. 3 Snow and ice route removal map in District 4, Kansas



1 routes, including multi-lane roads with more than 3000 vehicles daily; (b) Priority 2 routes, including two-lane roads with 1000–3000 vehicles daily; and (c) Priority 3 routes, including two-lane roads with less than 1000 vehicles daily. Current fleet size of winter operations for snow and ice route removal includes 90 available plow trucks with tandem and same size spreader units.

4.2 Fleet Optimization Model Development

The fleet optimization tools for winter snow and ice route removal operations include ArcGIS, a software package built upon a GIS platform with geodatabase management applications developed by Esri–GIS company based in California, USA, and its extensions. ArcGIS is capable of digitally producing optimized snow and ice routes in terms of GIS-based maps and allows users to investigate route conditions and conduct analyses based on transportation networks [4]. The software platform can handle complex optimization algorithms without requirements of profound coding or programming skills from end users, which helps transportation personnel implement the optimization outcomes easier. This study developed a fleet optimization model using ArcGIS and its Network Analyst extension and the Vehicle Routing Problem toolset. The parameters of the fleet optimization model include (1) total travel time—the time to complete a full treatment cycle for a SNICE route, which is the sum of treating time, deadhead time, and refill time of each treating cycle, (2) deadhead time—the time to drive to and from the treating area; (3) treating time—the time to drive and treat the SNICE route, calculated by the lane miles treated over the treating speed; (4) refill time—the time to refill the truck at the facility; and (5) LOS cycle time—the total time that requires the truck to leave the facility, treat the assigned snow and ice routes, return to the facility, and then refill to get ready for the next treating cycles.

Prior to the fleet optimization process, a GIS snow and ice route network dataset was created using the Network Analyst extension, and the snow plowing points were set up along all the snow and ice routes in the network using the Vehicle Routing Problem toolset. The fleet optimization process started with determining the efficiency of each snow-plow truck using the GIS base-map and Eq. 1.

$$\text{Individual truck efficiency} = \text{Treating time}/(\text{Treating time} + \text{Deadhead time}) \quad (1)$$

The truck efficiency represents the variation of the deadhead time spent within a treating cycle of a snow and ice route. The truck efficiency increases when there is a minimum of deadhead time needed to treat a snow and ice route. Based on the calculated efficiency results, the least efficiency truck was removed, and the base-map was re-created to accommodate the removed truck. The process of removing the least efficiency truck and re-creating new base-maps was repeated until it hit the threshold of the satisfied LOS percent that needs to be maintained.

The results of the fleet optimization model were compared with the thresholds included in the LOS documents of District 4, including the treating speed priorities and LOS cycle time priorities of each snow and ice route. The treating speeds (mile per hour) include three route categories: Priority 1 with 35 mph, Priority 2 with 25 mph, and Priority 3 with 25 mph. The LOS cycle time requirements (minutes) are shorter for high priority routes and longer for low priority routes; specifically, Priority 1 with 60 min, Priority 2 with 90 min, and Priority 3 with 120 min. The salt application used under normal conditions for each treating cycle is kept at 250 lbs/ln mile. Accordingly, the maximum number of operational trucks that could be removed was determined. This iteratively optimizing process should yield enough data to determine changes in the snow and ice route network to accommodate the removed trucks and assist winter maintenance personnel in monitoring and allocating their limited resources to essential maintenance operations. It is noted that the trucks treating Priorities 2 and 3 routes were removed before removing the trucks treating Priority 1 routes. The current network of snow and ice routes in District 4 includes 70 Priority 1 routes, 41 Priority 2 routes, and 32 Priority 3 routes.

5 Results

After multiple iterations of removing the least efficiency trucks and re-creating new base-maps of snow and ice routes, the fleet optimization model ended up with the maximum of four trucks that could be removed from the current fleet within District 4 while the satisfied LOS percent (79.72%) was maintained.

Table 2 Snow-plow fleet optimization results

Performance metrics	Fleet size (count)	Total travel time (minute/cycle)	LOS satisfaction (%)
Current snow and ice route removal	90	8113.60	79.72
Optimization result	86	6653.60	79.72
Difference (optimization versus current)	−4	−1460	0

Table 2 shows the fleet optimization results and comparisons with the current snow and ice removal practices within District 4. As a result, the fleet size needed to treat all 143 snow and ice routes was reduced from 90 to 86 trucks. A total of four plow trucks were removed from four sub-areas 411, 414, 422, and 443. The optimized base-map also shortened the total travel time to treat all snow and ice routes at once with a time saving of 1,460 min (approximately 24.3 h) for one treating iteration. The current satisfied LOS percent was also maintained at 79.72%.

The results provide recommendations for the minimum number of plow trucks required at each facility to maintain the current LOS at each snow and ice route in the network for winter maintenance operations. Based on the results of this study, KDOT may be able to adjust the routing of its fleets of snow-plow trucks for snow and ice removal, creating a more efficient operation and possibly reducing the number of trucks required for winter maintenance operations.

6 Conclusion

This study aimed at supporting KDOT's winter maintenance operations on snow and ice control activities with possible savings in both equipment and labor costs by developing a snow-plow optimization plan using modern technologies and modeling techniques. With the budget constraints and increased public demand for safe travel routes, the optimization plan can help KDOT efficiently allocate limited resources to maintain all snow and ice routes in an economic, safety, and reliability manner. A GIS-based software platform was utilized to develop a fleet optimization model for snow and ice route removal operations within District 4, Kansas, USA. The developed optimization model created an optimized base-map for 143 snow and ice routes within District 4 to save four plow trucks and approximately 24.3 h for one treating iteration while the satisfied LOS requirement of 79.72% was maintained. The optimization results enable KDOT personnel to justify the fleet size required at the selected District and improve productivity and safety in snow and ice route removal practices. Implementations of the developed fleet optimization model in other Districts within the State of Kansas after conducting the pilot study in District 4.

The contribution of this study includes developing a GIS-based snow-plow fleet optimization model to support winter maintenance operations on snow and ice route removals in District 4, Kansas. Expected benefits from the implementation of the optimization results include (1) cost savings from the optimized fleet size and (2) time savings to treat all snow and ice routes in the network. Successfully implementing the results of the developed optimization model may also increase safety for drivers traveling during snow events. Risks of accidents related to extreme weather conditions can decrease by treating the snow and ice routes in a shorter amount of time. This study also sheds light on the applicability of the GIS technology in assisting transportation management problems and operational considerations. The results of this study facilitate the automation of snow-plow optimization processes using ArcGIS software packages and its extensions in providing satisfactory services during snow and ice events.

Acknowledgements The authors would like to thank the Kansas Department of Transportation, especially Mr. Clay Adams, Director of Field Operations, and Mr. John Hrenak, District Maintenance Engineer, for their essential helps and supports with data collection, model development, and verifications.

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Agent-Based Modelling as a Decision-Support System for Project Delivery Methods

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1 Introduction

Achieving a successful project within the allocated budget and planned schedule is the goal of all decision makers in the architectural, engineering, and construction (AEC) industry [7]. However, the construction industry is full of inefficiencies, eventually leading to cost overruns, time delays, and poor end products [10]. These inefficiencies can be reduced to a large extent if an appropriate project delivery method (PDM) is chosen at an early stage in the project. Several PDMs have been developed throughout the years. The four most used methods are Design-Bid-Build (DBB), Design-Build (DB), Integrated Project Delivery (IPD), and Construction Management at Risk (CMAR). Poor selection of a PDM might result in an end product that does not meet requirements. Each project must be evaluated to determine which of the various methods would produce the best results for an owner [14, 15, 22]. Some owners decide on a PDM according to the team's experience and only consider the characteristics of the individual project without considering the company's strategy [18]. While there is no perfect project delivery option, one method may be better fit than another based on the specific requirements of a construction project [14, 15, 22]. Various factors including the specific owner, project, and team selection considerations should be considered when choosing the appropriate delivery method. While there is growing research in the PDM selection process, this research focuses on the need to help the owner make that critical decision based on factors that are unique

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S. Walbridge et al. (eds.), *Proceedings of the Canadian Society of Civil Engineering Annual Conference 2021*, Lecture Notes in Civil Engineering 247,
https://doi.org/10.1007/978-981-19-0968-9_39

to the organisation and project. This paper presents a decision-support system for PDMs. The factors that most impact the selection process according to the literature are identified. Then, agent-based modelling and simulation (ABMS) are used to model the delivery method selection process. After the user inserts the project details, the model calculates and displays the score of each PDM for the presented project. A virtual application is used to verify the model and display different results. Finally, the conclusion and future work are presented.

2 Literature Review

2.1 PDM Selection

Many research endeavors focus on assessing and comparing DB, DBB, CMAR, and IPD based on different factors. Over the last few decades, several approaches have been developed to help owners select the most suitable PDM for their project [12]. In a study comparing DB and DBB for 67 projects, [11] found that DB has an advantage in time savings, but it was not better than DBB in terms of cost reductions or productivity increases. Mahdi and Alreshaid [14, 15, 22] examined the compatibility of various PDMs with specific types of owners and projects using Analytical Hierarchy Process (AHP) based on high degree of technical factors and low construction costs. Mostafavi and Karamouz [17] developed a decision-making system to select a convenient PDM for project success. Moon et al. [16] gathered actual construction data from a multifamily housing project and developed a selection model for the owners to choose the right delivery method based on their needs, project characteristics, and external environment. Tran and Molenaar [22] used a survey based on completed cost and schedule risk analysis to identify 39 risk factors related to the project delivery selection process for projects worth more than $100 million. El Asmar et al. [6] carried out statistical analysis of data collected from 35 completed construction projects to compare the performance of IPD with other PDMs. Chakra and Ashi [2] evaluated the performance of several DB and DBB projects by identifying seven performance indicators such as cost, schedule, quality, risk, and safety. The results showed that DBB performs better in terms of time, quality, and safety; however, DB has better performance in terms of cost, communication, and risk.

2.2 ABMS

A Simulation, as defined by Binhomaid [4], is a computer-based imitation of a system through which its behavior may be better understood. The importance of simulations lie in their ability to work and behave as the original systems, especially when experimenting with the original system is too expensive, impractical, or time-consuming. Simulation applications are numerous, ranging from project management and economics to hospitals, airports, and supply chains [23]. Simulations include three different approaches: system dynamics, discrete-event simulation, and ABMS [23]. ABMS is the approach adopted in this paper. In ABMS, a collection of autonomous decision-making entities is used to model the system under study [5], and it is aimed at analyzing a complex system by building imaginary agents to mimic the behaviors and interactions of the entities in the original system [24]. The three main components of an agent-based model are the agents, their relationships, and their environment [3]. In construction, Teicholz was the first to develop a simulation model to study and reflect construction systems and processes [1, 20]. Since computer simulation helps in supporting decisions needed in the design and implementation of construction processes [9], ABMS in construction has been used for various purposes. In 2016, a study computed realistic task durations by taking workers' fatigue into consideration [19]. In 2020, a study used ABMS to optimize the workflow of robotic steel and concrete 3D printers [3]. While the uses of ABMS in construction are numerous, not much research exists using ABMS for construction contracts and contract administration. Therefore, this study's contribution lies in employing ABMS to contract administration by modelling the PDM selection process and aiding in the selection of the appropriate PDM for different projects.

3 Methodology

To achieve the goals of this study, the following structured methodology was used. First, a thorough literature review was conducted to identify and evaluate the factors affecting the selection of various PDMs. These factors were classified into six main areas and used to develop the conceptual model, which constitutes the second step of the methodology. The conceptual model was based on the identified problem, and it revolved around helping the owner in deciding on a PDM that was suitable for their project. To do so, the owner answered questions that were based on data gathered in the first step. As a third step, this conceptual model was implemented as a computational model in AnyLogic 8.6.0 software [8]. Finally, the model was verified by running it several times with different scenarios, and the results were documented.

4 Conceptual Model

It is worth mentioning that although the study is directed to the owner, its goal is to ultimately best serve the interest and purpose of the project. The owner should use the model with good intentions and without the intention of transferring all risks to the contractor.

Table 1 Factor areas

Owner	Project characteristics	Design characteristics	Regulatory	Risk	Others

4.1 Factors Affecting Project Delivery Method Selection

Choosing a PDM that is suitable for project needs plays a substantial role in ensuring a refined execution of construction processes and eventually a successful project. Many factors are involved in the selection of a PDM, making it difficult to reach a decision. To start the process, an owner would answer a set of questions pertaining to personal characteristics (e.g., leave of project management experience), to the project characteristics (e.g., the project schedule), and to the other areas shown in Table 1. Table 2 shows some of the most significant factors that affect the PDM selection, according to the literature. The owner is asked to provide their answer as a rank on a scale from 1 to 5; i.e., a rank = 1 for the budget means a tight budget and a rank = 5 means a high budget. The questionnaire style is inspired by a study by from Liu et al. [13].

4.2 Relative Importance, Rank, and PDM Score

After identifying the most significant factors that affect the PDM selection process, the relative importance of each factor across all PDMs must be determined. Ranking the criticality of some factors was based on questionnaires with experts. For instance, [22] rank unexpected utility encounters (UUE) factor as first out of eight critical risk factors in DBB, tenth out of ten in DB, and eighth out of eight in CMAR (first factor being the riskiest). Therefore, DBB is (1/8) × 100 = 12.5% favorable for dealing with UUE. The calculation of the relative importance (RI) of each factor is represented by Eq. 1 below.

$$\text{Relative Importance (\%)} = \frac{\text{Factor Rank}}{\text{Number of Factors}} \times 100 \tag{1}$$

After knowing the RI of the factor for each PDM, the values are normalized on a scale of 10–100 to have a systematic scale across all factors. The normalization of the RI is represented by Eq. 2.

$$\text{Normalized Relative Importance} = (100 - 10) \times \frac{\text{Relative Importance - Minimum Value}}{\text{Maximum Value - Minimum Value}} + 10 \tag{2}$$

Table 3 shows an example of the RI and the normalized RI for the UUE factor.

Table 2 PDM factors, descriptions, and codes of values

Factor	Description and Codes of Value
A. Budget (Touran et al. 2011)	The owner's allocated budget for achieving the project ***1=tight budget, 3=fair budget, 5=high budget***
B. Schedule (Touran et al. 2011)	How tight the project schedule is and the availability of time to finish the project ***1=tight schedule, 3=normal schedule, 5=relaxed schedule***
C. Delivery speed (Mahdi and Alreshaid 2005)	Whether project duration and its delivery speed are critical or ***1=speed not important, 3=speed important, 5=speed crucial***
D. Quality of work (Martin et al. 2016)	How much the owner is concerned about the quality of construction works ***1=less concerned, 3=concerned, 5=strongly concerned***
E. Experience with project management (Mahdi and Alreshaid 2005)	The level of experience of the owner with project management, design-related changes, regulatory changes, and change orders ***1=low experience, 3=some experience, 5=strong experience***
F. Green building certification (Touran et al. 2011)	The owner's interest in environmental aspects & in green building certificates ***1=not interested, 3=interested, 5=strongly interested***
G. Team integration (Mahdi and Alreshaid 2005)	The level of the owner's interest in having an integrated team ***1=not interested, 3=interested, 5=strongly interested***
H. Control level (Mahdi and Alreshaid 2005)	The level of control on the project (design, changes) the owner wishes to have ***1=low control, 3=some control, 5=high control***
I. Innovation (Martin et al. 2016)	Whether the owner prefers traditional or innovative ***1=traditional, 3=somewhat innovative, 5=highly innovative design***
J. Involving contractor in the design (Mahdi and Alreshaid 2005)	If the owner prefers having the contractor during planning and design phases ***1=not interested, 3=interested, 5=strongly interested***
K. Scope definition (Martin et al. 2016)	How clear the scope of work is ***1=ambiguous scope, 3=okay scope, 5=very clear scope***
L. Level of trust with the other stakeholders (Mahdi and Alreshaid 2005)	The owner's level of trust with other stakeholders (designer, contractor, D-B) ***1=low trust, 3=fair trust, 5=high trust***
M. Clarity of contract documents (Martin et al. 2016)	Whether the contract documents are crisp clear or include so much ambiguity ***1=ambiguous documents, 3=okay documents, 5=crisp clear documents***
N. Geotechnical investigation (Tran and Molenaar 2012)	The level of uncertainty around soil conditions and geotechnical investigation ***1=risky soil, 3=normal soil, 5=certain soil***
O. Unexpected utility encounters (Tran and Molenaar 2012)	The level of unexpected utility encounters and such uncertainties ***1=high encounters, 3=normal encounters, 5=low encounters***
P. Delays (Tran and Molenaar 2012)	The expected delays in reviewing and obtaining environmental approvals ***1=delayed approval, 3=normal approval, 5=fast approval***
Q. Third-party delays (Tran and Molenaar 2012)	The expected delays by third parties (such as subcontractors…) ***1=many delays, 3=normal delays, 5=few delays***

Table 3 Unexpected utility encounters relative importance

	DBB	DB	CMAR	IPD
Relative Importance of UUE (%)	12.5	100	100	90
Normalized RI on 10–100	10	100	100	90

Since the mentioned study does not tackle IPD, the relative importance of its UUE is estimated based on the literature. The results are logical since DB and CMAR are the most favorable methods to deal with unexpected utility encounters or risky soil conditions. The term "RI" will refer to the normalized RI through the remainder of this paper.

Not all factors are found to be ranked quantitatively in the literature, most factors are ranked qualitatively. Since the RI needs to be numerical, the qualitative rankings were transformed into quantitative ones. For example, it is found that delivery schedule is not a critical factor for DB and CMAR, but it ranks sixth out of eight risk factors in DBB [22]. This means that DB and CMAR score high for delivery schedule factor but DBB would score less. Accordingly, delivery schedule score can be valued as 10 for DBB, 55 for DB, 78 for CMAR, and 100 for IPD.

After obtaining the RI of all factors based on the literature, the owner chooses a rank for each factor for a specific project. The ranks range from a value of 1–5 (1 being the lowest and 5 being the highest).

The score of each PDM is obtained from the assigned RI values and the inserted ranks. It is the summation of the product of each factor's relative importance and rank (Eq. 3).

$$\text{PDM Score} = \sum (\text{Relative Importance x Rank}) \tag{3}$$

The maximum and minimum possible values of the PDM score are obtained from the maximum and minimum values of the rank. Since the maximum and minimum rank values are 5 and 1 respectively, the maximum possible value of the PDM score (based on the assigned RI values) is 6525, while the minimum is 940. To normalize the PDM scores to values between 0 and 10, Eq. 4 is used.

$$\text{PDM Score} = \frac{\text{Raw PDM Score - Minimum}}{\text{Maximum - Minimum}} = \frac{\text{Raw PDM Score - 940}}{6252 - 940} \times 10 \tag{4}$$

4.3 *Experience*

The experience of the project team in a certain PDM has an impact on the project performance. Therefore, the team's experience in each PDM is specified by the owner at the beginning of the simulation, and it ranges from 0 to 10. As the team completed new projects, their experience in the chosen PDM is increased by a value of 1. Equation 5 represents the variation of the experience with each project completion.

$$\text{Experience} = \text{Previous Experience} + 1 \tag{5}$$

4.4 Final Score

To assist the owner in selecting the appropriate PDM, the scores are calculated based on the PDM scores (obtained from RI and Rank) and the experience. Equation 6 represents how the score is calculated.

$$\text{Score} = (0.8 \times \text{ PDM score}) + (0.2 \times \text{ PDM experience}) \tag{6}$$

The weights can be adjusted according to the user's desire. If the user favors experience, they can increase its corresponding weight. According to Eq. 6, the scores range between 0 and 10. Since the score value will be used in the calculation of the duration, the lowest allowable value is 1 and the highest is 10. Therefore, Eq. 7 is used to normalize the score values and obtain the final score results for each PDM.

$$\text{Score} = (10 - 1) \times \frac{\text{Score - 0}}{10 - 0} + 1 \quad \text{where Score} = (0.9 \times \text{ score}) + 1 \tag{7}$$

4.5 Duration and Percent Deviation

The actual duration needed to complete the project based on the given inputs and the chosen PDM is calculated. Since the appropriate selection of a PDM can help in reducing the duration and vice versa, Eq. 8 is used to calculate the actual duration of project completion.

$$\text{Actual Duration} = \text{Planned Duration } \times \left(\frac{5}{\text{score}}\right) \tag{8}$$

According to Eq. 8, the best-case scenario occurs when the score is 10. In this case, the project duration will be halved. The worst-case scenario occurs when the score is 1, in which case the duration is multiplied by 5. It is important to note that these two scenarios are extreme "ideal" cases that do not occur. They are used for verifying the adopted calculation of the actual duration.

Finally, to assess the project performance in terms of schedule, the percentage of deviation from the planned duration is calculated according to Eq. 9.

$$\text{\% Deviation} = \frac{\text{Actual Duration - Planned Duration}}{\text{Planned Duration}} \times 100 \tag{9}$$

5 Computational Agent-Based Model

The PDM selection process is modelled using ABMS through a software called AnyLogic [8]. The model includes two agents: the project and the team. Both agents exist in the main environment and contain a set of variables and parameters that define their behavior and performance. A detailed explanation of each agent and its attributes is described below.

5.1 The Project Agent, the Team Agent, and the Main Environment

The project agent is represented in Fig. 1a. Each PDM is assigned a weight referring to each factor, and the duration of the project is determined by the user for each project. Once the user inserts the ranks for all factors, the score of each PDM is calculated and represented by the parameters "PDM_Score". At start-up, the project enters the "Initial_State", which activates a function to prompt the user to insert the team's initial experience in each PDM. Once done, a message is sent to the project to move through a message-triggered transition to the next state, "Unavailable". At a rate of once per year, a new project is generated, and the project moves through the rate-triggered transition into the "New Project" state. Then, the user is prompted to rank the factors and to choose the desired PDM. Once the user's inputs are inserted, the project moves into the "In_Progress" state through a message-triggered transition. It stays in this state until it receives a new message that the project is completed, which is when the project moves back to the "Unavailable" state. This cycle goes on until the team completes 10 projects.

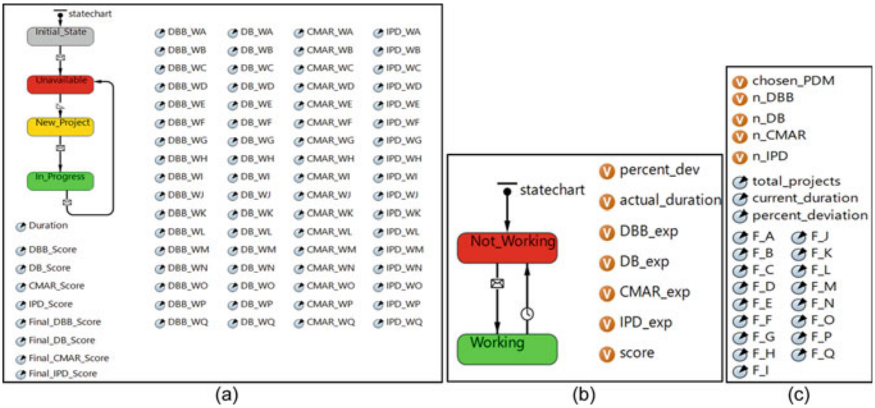

Fig. 1 Statecharts, parameters, and variables of the project (**a**), team (**b**), and main environment (**c**)

The team agent (Fig. 1b) enters the "Not_Working" state at start-up. Once it receives a message from the project agent to start working, it moves through the message-triggered transition into the "Working" state until the activity is completed. After the project is completed, the team agent moves through a timeout-triggered transition back to the "Not_Working" state and waits for another project to be generated. The initial experience values inserted by the user at start-up are saved in the "PDM_exp" variables. After the team completes a project, their experience in the chosen PDM is increased by 1. The experiences in each PDM keep increasing as the team completes new projects until they reach a maximum value of 10. Additionally, after the team completes a project, the actual duration needed for the completion of the project and the percent deviation from the planned duration are stored in the "actual_duration" and "percent_dev" variables, respectively.

The main environment contains the team agent, the project agent, a set of variables and parameters, a plot, and a graphical user interface (GUI) through which inputs are inserted and results are displayed. In Fig. 1c, the variable "chosen_PDM" contains variables to store the PDM chosen by the user in the first question through the GUI. Every time a certain PDM is chosen, its counter (n_DBB, n_DB, n_CMAR, or n_IPD) increases by 1. The parameter "total_projects" stores the number of projects completed by the team, while the parameter "current_duration" stores the duration of the latest completed project. The "percent_deviation" parameter stores the percent deviation from the planned duration for each project. The parameters "F_A", "F_B", …., "F_Q") store the ranking of each factor as specified by the user.

5.2 *The Simulation Runs*

Once the simulation is run, the user is prompted to insert the team's previous experience in working on each PDM. These values are inserted only once at the beginning of the simulation, and they are automatically updated every time the team completes a project using a specific PDM. Then, they click on the "DONE" button. After the initial experiences are entered and stored in their respective variables, the GUI displays a "Waiting for a project" message. Once a new project is generated, the user is asked to insert the project's details, including the importance of certain factors and the planned project duration. All inserted data is stored in the model's variables and parameters to be used in the calculations. Once all data is inserted, the user clicks on the "INPUTS INSERTED" button. Then, the PDM scores are displayed along with a prompt to select the chosen PDM. The user can select the best PDM based on the calculated scores, and they click on the "PDM CHOSEN" button. The project is then initiated and a "Working on the project" message is displayed. After the project is completed, the "durations", "% deviation", and "chosen PDM" plots and charts are automatically updated with the new duration, percent deviation, and the number of times each PDM has been chosen. This process continues until ten projects are completed. At this point, the plots show all ten values of durations and percent deviation to allow for comparison and analysis, in addition to the number of times each PDM has been chosen.

6 Virtual Application

To verify that the model was built correctly, a virtual application was performed. In this application, the team is assumed to have previously performed 4 DBB projects and 2 DB projects. Thus, the initial experience values are set as 4, 1, 0, and 0 for DBB, DB, CMAR, and IPD, respectively, as shown in Fig. 2.

Once a new project is generated, its details were added, including the factors' ranks (A → Q) and the planned duration. A set of 10 virtual projects (P1 → P10) with their details and durations is shown in Table 4.

Figure 3a shows an example of the GUI where the user is asked to insert the last project's details, and Fig. 3b shows how the scores are represented and the user is asked to choose the best PDM.

Finally, Fig. 4 shows the final plots and chart after all 10 project details are inserted and their respective PDMs are chosen. Figure 4a depicts the plot of the actual durations of the 10 projects. These durations depend on the planned durations and the scores of the PDMs obtained from the model. Figure 4b is a plot of the % deviation of the actual durations from the planned ones. As the plot shows, the % deviation decreases as the number of projects done by the owner increases. This shows that as the owner is doing more projects, they are getting more experienced with the different chosen PDMs. The % deviation ranges from positive values to negative values. The negative values imply that the actual duration is less than the planned one, which is favorable in construction projects as it denotes cost and time savings. The last plot shows the PDMs selected for the 10 projects. The CMAR turned out to be the most preferred method for this specific owner's 10 projects.

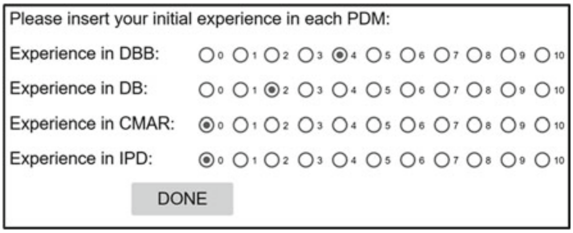

Fig. 2 GUI prompt to insert initial experiences in each PDM

Table 4 virtual projects data

	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10
A. Budget	1	1	5	4	4	4	5	4	5	4
B. Schedule	1	1	5	3	4	3	5	3	3	5
C. Delivery speed	1	4	4	5	3	1	3	5	4	5
D. Quality of work	1	1	2	5	1	2	2	5	5	5
E. Experience in project management	1	2	4	5	1	2	1	5	3	5
F. Green building certification	1	2	4	5	3	1	3	5	2	5
G. Team integration	1	2	4	5	1	1	4	5	4	5
H. Control level	1	1	5	2	4	5	5	4	1	4
I. Innovation	1	1	3	5	1	5	4	5	2	5
J. Involving the contractor in the design	1	5	5	5	5	1	5	3	3	5
K. Scope definition	1	1	5	1	4	5	5	2	5	5
L. Level of trust with other stakeholders	1	1	1	5	2	5	4	5	4	5
M. Clarity of the contract documents	1	2	5	5	4	5	5	4	5	2
N. Geotechnical investigation	1	1	5	3	4	5	5	1	2	3
O. Unexpected utility encounters	1	5	5	4	4	1	4	5	3	2
P. Delays	1	1	5	1	4	5	5	5	1	1
Q. Third-party delays	1	1	2	5	2	2	3	5	4	5
Planned Duration	12	20	18	36	30	25	52	41	16	60
Chosen PDM	DBB	DB	CM	IPD	CM	DBB	CM	IPD	CM	IPD

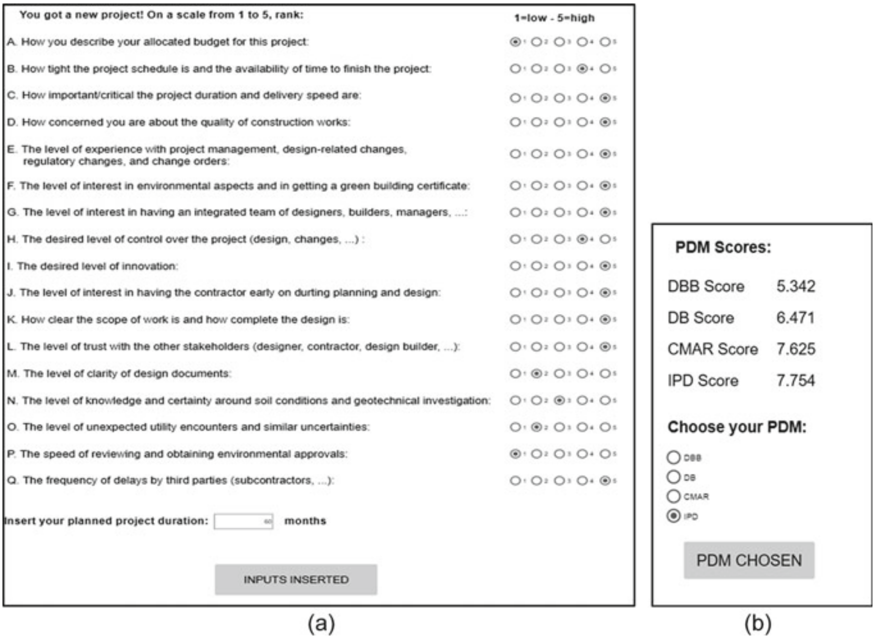

Fig. 3 GUI prompts to insert project details (**a**) and chosen PDM (**b**)

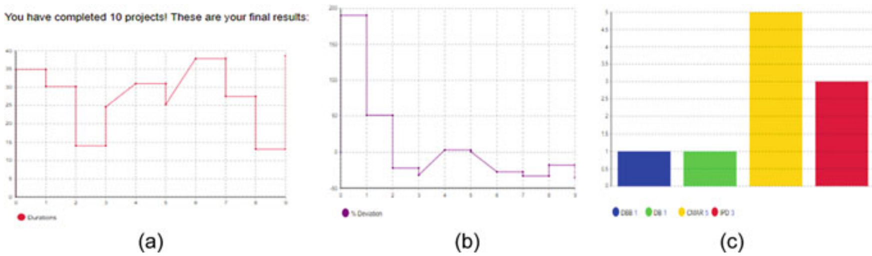

Fig. 4 Final durations (**a**), percent deviations (**b**), and chosen PDM results (**c**)

7 Conclusion

As one of the most critical decisions made by an owner is choosing a proper delivery method, developing a decision-support system to aid the owners in making this decision is crucial. While several researchers have developed different studies in this regard, no study has yet been conducted using ABMS to simulate this decision-making process. This study presents a novel contribution by analyzing and evaluating various factors that affect the PDM selection process to be included in an agent-based model. Factors were classified into six categories and given "relative importance" values to quantify the criticality of each factor in each PDM. This value is combined with "ranks" inserted by the user to obtain a PDM score. The PDM score, along with the team's previous experience in each PDM, is used to obtain a final score which directs the owner toward the most suitable choice of PDM. It gives the owner a glimpse of how the project will progress if a certain PDM is chosen. After several projects are inserted and their respective PDMs are chosen, a final chart showing the results of all projects is presented. This allows for better analysis and understanding of how PDM selection affects the success of the project. Despite the mentioned contribution, some research limitations are noted. One limitation is that some factors affecting the PDM selection process were subjectively quantified. This was due to the unavailability of research studies that accurately quantify the impact of some factors on the PDM selection through case studies or in-depth analysis. Another limitation is the developed equation for the final duration. It was assumed that a score of 5 would yield an actual duration equal to the planned duration, while higher scores yield shorter durations and vice versa. This assumption may be improved through more intricate calculations or proven case studies. For future work, it would be a step forward to estimate the actual duration using Program Evaluation and Review Technique (PERT) analysis, which can be used to examine the tasks in a schedule. This would generate precise and reliable durations that can assist owners in accurately predicting project schedules. Another recommendation would be assessing all factors' rankings based on surveys and questionnaires led by experts. This would allow for better quantification of relative importance values. Finally, the model can be applied to case study projects to validate that the model serves the intended purpose.

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Green and Sustainable Certifications for Existing Buildings, the Example of the Upgrading to Standards and Heritage Restoration of Montreal City Hall

Flavie Plourde-Mainville and Claudiane Ouellet-Plamondon

1 Introduction

In order to actively participate in sustainable development objectives and contribute to the fight against climate change, the City of Montreal wishes to achieve carbon neutrality by 2050, with reference to its Climate plan 2020–2030 [1]. To achieve this goal, several commitments have been put in place in recent years, including the Sustainable development policy for the City of Montréal's buildings issued in 2009 [2]. This policy requires that all new construction or major renovations of its buildings meet the minimum LEED-Gold (mandatory certification) and LEED-Silver (non-mandatory certification) criteria respectively, considering that 20% of the city of Montréal's GHG emissions are attributable to the operation of buildings [2]. In this context of reducing greenhouse gas emissions, the upgrading to standards and heritage restoration project for Montreal city hall project is a good example of the application of the approaches put in place and the potential for green and sustainable performance of existing buildings. In addition to bringing fire, electrical and mechanical systems up to standard, restoring and enhancing heritage elements, and providing occupants and users with a healthy environment and efficient, high-performance facilities, this project aims to obtain LEED Existing building: operation and maintenance (LEED EBOM) v4.1 Gold level.

Considering the Montreal city hall as a flagship building of the municipal administration, the present administration wishes to demonstrate to its various executives that such a certification based on operational performance is feasible and viable in the long term. To date, several green and sustainable certifications are offered for the

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S. Walbridge et al. (eds.), *Proceedings of the Canadian Society of Civil Engineering Annual Conference 2021*, Lecture Notes in Civil Engineering 247,
https://doi.org/10.1007/978-981-19-0968-9_40

improvement of building performance. Considering that this field is developing and proving its worth in the form of construction projects of multiple nature and scale, the first objective is to define and understand the possibilities offered to existing building renovation projects. New building and green performance are often linked, but LEED, BOMA BEST, Living Building Challenge, Zero Carbon and WELL certifications apply equally well to existing buildings. By defining what each of these certifications represent (objectives, nature of the concepts, level of complexity, etc.), it will be possible to meet the second objective, which is to understand why LEED EBOM certification was considered the most suitable for the sustainable development objectives of the city hall project. Subsequently, considering the WELL certification, focused on the well-being and health of the occupants, as a very good complement to a certification aimed at ecological performance, the third objective is to conduct a preliminary analysis of this certification in order to validate its potential application to the new Montreal city hall building. Finally, in the current context of the Covid-19 pandemic, we will identify the initiatives and adaptations to the Montreal city hall project that have been put in place since last year, in order to ensure an additional level of health security for the users of the renovated building.

2 Methodology

2.1 Montreal City Hall Project

Since its inauguration in 1878, its reconstruction between 1923 and 1926 and following various works carried out over time, Montreal city hall no longer meets the requirements and standards of buildings. Indeed, the fire, electrical and mechanical systems have reached a significant level of obsolescence. As the City Administration's flagship building, the upgrading to standards and heritage restoration of Montreal city hall is a major project that allows for strategic management of asset maintenance, building enhancement and the integration of new sustainable development regulations and standards (Fig. 1).

In 2015, the project management team set up the project to bring the city hall up to standard and restore its heritage. To carry out this major project, contracts were awarded to various professionals, including a first contract to the team responsible for preparing the plans and specifications (a team composed of architects, engineers and other specialists) and a second to a general contractor for construction management. In fact, for the first time for the City of Montreal, this project is being carried out in management mode in order to transfer construction management to a general contractor, considering the complexity of the project. Thus, the renovation work is subdivided into distinct lots and the realization of each one is entrusted to contractors by launching a call for tenders for each lot. These construction contracts are therefore issued by the City, but managed by the construction manager.

Fig. 1 Montréal city hall. From https://upload.wikimedia.org/wikipedia/commons/6/68/Hotel_de_ville_de_Montreal_42.JPG. Free for commercial use

In addition to the professionals, the construction manager and specialized contractors, it is important to mention that the project integrates, from the beginning of the design, different representatives of the building users in order to optimize, according to the identified needs, the design of the new city hall. This translates into the application of the Integrated Consultation Process (ICP) to the project.

The construction's phase of the project to bring Montreal city hall up to building standards and restore its heritage began in 2019. In the spring of that same year, the occupants of city hall building moved to the neighbouring Lucien-Saulnier building. The construction then followed quickly and, to date, construction is underway and is currently scheduled for completion in 2023.

2.2 Review of Certifications for Existing Buildings

In order to achieve the above-mentioned project objectives, the first step was to carry out research to identify and characterize the various ecological and sustainable certifications available in the field of existing buildings, based, among other things, on prior knowledge. Once the available certifications were identified and the reference documents collected, a detailed review of the reference guides and official certification websites was necessary in order to define what precisely the certifications consist of, to identify the components of each one, their criteria, their constraints to be respected to meet them and their scoring system. From this research, a global portrait of each certification was drawn, in addition to better understanding the choice of LEED EBOM certification for the Montreal city hall upgrading to standards and heritage restoration project.

Subsequently, considering the nature and objectives of each of the certifications identified, it was possible to validate the potential application of WELL certification to the Montreal city hall project. Indeed, this certification stands out for its objectives of occupant health and well-being, which are closely linked, among other things, to building performance elements in terms of HVAC (heating, ventilation and air conditioning) system components, water quality and the quality of materials components (architectural components, construction materials, maintenance products, etc.) [3].

2.3 *Preliminary Analysis of the WELL Certification*

WELL certification appears to be an ideal complement to the LEED existing buildings certification for the city hall project, however, a validation process was required to confirm whether the project is eligible for WELL certification. This is how the second step was initiated, namely the preliminary analysis. This step is composed of two parts.

2.3.1 Part 1—Preliminary Overview of WELL Criteria

Part 1 consists of a preliminary overview of all the criteria of the ten WELL concepts. The objective is to carry out an overview of each of them, to carry out a first sorting of the criteria that cannot be met and, in parallel, to identify all the information to be validated. In this component, it was also necessary to identify resources who are active in the Montreal city hall project and who could answer the questions raised during the overview of the criteria. The list of these resources is presented in Table 1.

Once these people were identified, meetings were planned with them and the information collected was compiled from a database. This database was subdivided based on the ten WELL concepts and contains all the information necessary for the analysis, such as the criteria, the information to validate, the stakeholders to question, the answer (yes/no), the score and the information supporting the answer.

Table 1 Resources involved in the city hall project, part 1 of the preliminary analysis

Resources
Employee of Montreal City Hall and the City of Montreal
Architect, member of the design team assigned to the city hall project
Mechanical engineer, member of the design team assigned to the city hall project
WELL and LEED certified professionals

Table 2 WELL certification levels, reference scoring system

Total score	Minimum score per concept	Certification level
40 points	0	WELL Bronze
50 points	1	WELL Argent
60 points	2	WELL Or
80 points	3	WELL Platine

2.3.2 Part 2—Detailed overview of WELL criteria

Subsequently, using the updated database, a second and more detailed overview was conducted to confirm or deny full or partial compliance with the criteria. Firstly, it should be considered that in order to obtain the minimum level of certification WELL Bronze, it is necessary to meet all of the prerequisites and confirm that they are or can be met. It was therefore necessary to study all the characteristics of the prerequisites for each concept based on the WELL certification guide [4]. Considering the status of preliminary analysis, the objective is also to identify the elements to be improved or implemented for the prerequisites that the Montreal city hall project does not quite meet at the moment.

Subsequently, considering the information gathered from the stakeholders, it was possible to identify the criteria called “optimization characteristics” that the Project meets, or could potentially meet according to certain recommendations, in order to achieve a higher level of certification. Each optimization characteristic allows a certain number of points to be collected and it is these points that allow the Project under study to reach a higher level of certification. These levels of certification and associated scores are presented in Table 2. The choice of these additional criteria must be based on City of Montreal’s policies and programs already in place as well as on the specifics of the improvements made to the building through the major renovations currently underway. Therefore, it is important to pay attention to the choice of optimization features, since if the Montreal city hall project is not already able to meet them, changes of nature and scope, sometimes significant, may be required.

With reference to Table 2, the selection of the optimization characteristics to be respected must therefore ensure that the Project achieves a minimum of 1 point and a maximum of 12 points for each of the ten concepts [3]. Finally, depending on the project’s ability to meet all of the prerequisites and optimization characteristics, which may, at the preliminary analysis stage, be partially or partially met, it is possible to decide on a WELL certification level if Montreal City Hall ever wishes to comply with it.

3 Result and Discussion

3.1 Review of Certifications for Existing Buildings

Following the literature review on green and sustainable certifications applicable to existing buildings, it is possible to see that the certifications identified are mostly certifications focused on the energy performance of buildings. It is possible to group these certifications into two categories. First, there are certifications applicable to the real estate management of existing buildings, whose main objective is to achieve the ecological efficiency of buildings through the implementation of green and sustainable policies. These certifications are LEED EBOM and BEST Sustainable Workplaces Program. We also find certifications more commonly applicable to the renovation of existing buildings or the construction of new buildings. These certifications are BOMA BEST Single Building stream, Living Building Challenge, Zero Carbon and WELL. These certifications are summarized in Table 3.

LEED EBOM is a certification adapted to existing buildings and interior spaces. The certification is based on 7 categories of requirements: location and transportation, sustainable site, water efficiency, energy and atmosphere, materials and resources, indoor environmental quality and innovation [5]. In order for a project to be certified, it is necessary to compile building performance data over a minimum period of 1 year.

Table 3 Summary of green and sustainable certifications for existing buildings

Certifications	Main objectives	Categories
LEED EBOM	Green and sustainable operation and maintenance programs and policies	Green operations and maintenance
BOMA BEST Sustainable Workplaces Program	Sustainable property management based on environmental and procurement policies	Environmentally friendly property management
BOMA BEST Single Building stream	Energy efficient property management for all types of existing buildings	Energy efficiency
Living Building Challenge	Buildings that contribute to restoring the natural environment while allowing the community to reconnect with nature	Energy efficiency
Zero Carbon	Buildings whose operations are low carbon, with the aim of achieving carbon neutrality	Energy efficiency
WELL	Application of occupant health and well-being concepts in building design	Health and Wellness

Once certification is obtained, it is valid for a period of three years. Building managers must therefore maintain their database and ensure the continuity of the measures put in place in order to obtain LEED EBOM certification again.

The BOMA BEST Sustainable Workplaces Program is also a certification for existing buildings or interior spaces and is renewable every three years [6]. This certification is based on procurement and environmental policies. The requirements of the procurement policies in place are, for example, to demonstrate concern for the procurement of sustainable and responsible equipment through Energy Star, EcoLogo, FSC, etc. certifications [6]. Subsequently, through environmental policies (water, energy, waste management, etc.), BOMA BEST Sustainable Workplaces Program certification requires that the spaces evaluated be certified by an ecological certification program, which distinguishes this certification from others, since its validity depends, among other things, on prior ecological certification. In the same BOMA BEST category is the Single Building stream, which aims to certify a building on the basis of its energy performance, i.e. its energy intensity, water use intensity and Energy Star performance rating [7]. For this certification, the building under study must have an occupancy rate greater than 70% over a consecutive 12-month period in order to be eligible for the higher levels of certification [7]. Otherwise, only the basic level (Certified level) can be obtained.

The Living Building Challenge (LBC) certification, on the other hand, aims to demonstrate that a built environment can truly contribute to restoring the natural environment, while allowing the community to reconnect with nature. The LBC certification is applicable to all types of buildings (new construction, renovation of existing buildings, interior spaces), is built around seven categories of requirements (called petals) and is obtained only once after a 12-month commissioning period [8]. The LBC certification presents an interesting particularity contrary to other green certifications. The latter adapts to the regions, the environment and the social context of the projects. This adaptation is reflected in the Living Transect [8], which allows exceptions to the requirements to be applied depending on the context of the projects.

For its part, the Zero Carbon Building (ZCB) certification aims to certify buildings that are efficient and low in carbon emissions. This certification offers two possibilities, Carbon Zero Design and Carbon Zero Performance. The Performance certification focuses on the zero-carbon operation of existing buildings, unlike the Design certification, which covers their construction (new or renovated). The principle of ZCB certification is to achieve carbon neutral buildings by measuring intrinsic and operational carbon emissions, while considering the carbon emissions avoided, for example through the use of green electricity, the implementation of an offset plan or other mitigation measures [9].

WELL certification aims to integrate the notions of well-being and health of occupants into a sustainable development approach, unlike known ecological certifications that put forward the energy performance of buildings [4]. This translates into the quality of the design and layout, the quality of the interior environment, the building's mechanics and the well-being of the occupants in all its facets; healthy living habits, working conditions, physical activity, nutrition and more [10].

Table 4 Validation of the application of certifications for identified existing buildings

Certification	Applicability to the Montreal city hall project	
LEED EBOM	Yes	Certification already applied to the project
BOMA BEST Sustainable Workplaces Program	Yes	Provided LEED EBOM certification is obtained
BOMA BEST Single Building stream	Yes	The objectives of this certification are oriented towards certain project objectives, but mainly focused on specific energy performance objectives
Living Building Challenge	Yes	The objectives of this certification are oriented towards certain project objectives, but are more restrictive and complex
Zero Carbon	No	The objectives of this certification are not aligned with the objectives of the project
WELL	Yes	The objectives of this certification are oriented towards certain project goals and could be a complement to LEED EBOM

Considering the objectives of each of these certifications, it would have been possible to apply the majority of them to the Montreal city hall major renovation project, as can be seen from Table 4. However, the level of complexity and the concordance between their objectives and those of the project favoured the selection of LEED EBOM certification, without necessarily involving major expenditures in terms of new construction. Indeed, at the beginning of the project, there was talk of considering LEED EBOM and LBC certification. However, the LBC certification was particularly restrictive in terms of the selection of construction materials (certified materials, local suppliers, etc.), which was an important issue regarding the feasibility of this certification. On the contrary, LEED EBOM mainly targeted the building operation phase, which was more in line with the Montreal city hall project objectives.

Finally, it can be seen that the WELL certification is the only certification for existing buildings that focuses on the aspect of well-being and health of the users. This is why WELL certification seems to be an enlightened and innovative choice to complement the sustainable aspect of the Montreal city hall building. This complementarity offers Montreal City Hall the opportunity not only to demonstrate its ecological capabilities by improving its operations and maintenance management methods, but also its ability to optimize its performance in terms of well-being in the workplace, linked to healthy and optimal working conditions for all of its users.

3.2 Preliminary Analysis of the WELL Certification

Considering the added value that WELL certification seems to offer, it is essential to analyze the feasibility of applying it to the upgrading to standards and heritage restoration of Montreal city hall project. First of all, the first essential verification, as mentioned above, is the validation of compliance with the prerequisites. Following a detailed analysis of these prerequisites, it is possible to affirm that approximately 50% of the prerequisites are currently met. Indeed, the prerequisites are globally respected. However, certain criteria must necessarily be validated by carrying out tests (upstream optimization to be planned or analysis of what exists), which prevents a decision on the acquisition of these characteristics. However, there is no major doubt as to their compliance. Overall, it is considered that the prerequisites could be met in their entirety, while still considering the adjustment of certain elements, particularly with regard to internal policies and programs in place. This would result in the achievement of the basic level of WELL certification, the WELL Bronze level. Subsequently, with a view to improving the basic certification, the performance optimization characteristics were reviewed in detail to confirm the possibility of obtaining a minimum of 1 point for each of the ten concepts. Certain optimization characteristics were therefore confirmed as having been acquired by the project and other characteristics were identified as potentially met, provided adjustments were made. These adjustments may be related, for example, to space planning, components of the various mechanical systems, or existing policies and programs. The results of the detailed preliminary analysis of each of the optimization characteristics are presented in Table 5 and all of the points identified are grouped by concept.

From Table 5, it is possible to see two main elements. First, the Montreal city Hall project would be able to obtain a minimum of 1 point for each concept, which would allow it to reach the WELL Silver level. Reaching this level is confirmed on the basis of eight out of ten concepts with one point acquired according to known data. The Water and Acoustic concepts are the ones that could prevent the achievement of the Silver level, considering that some characteristics must necessarily be confirmed by

Table 5 Results of a detailed preliminary analysis of the WELL optimization criteria for the Montreal city hall project

Concepts	Minimum acquired score of 1 point (yes/no)	Potential score (points)
Movement	yes	5
Air	yes	1–3
Community	yes	1–2
Sound	yes (after testing)	1–2
Thermal Comfort	yes	2–6
Water	yes (with improvements and/or features validation)	1–2
Mind	yes	1–2
Light	yes	1–4
Materials	yes	1–2
Nourishment	yes	1–3
Innovation	N/A	1–5

the realization of tests. In fact, one of the last steps of the certification is the realization of tests, by a representative of the International WELL Building Institute (IWBI), directly realized in the spaces of the building being certified. These tests validate, for example, the air quality, water quality, reverberation, acoustic performance and more in order to confirm compliance with the prerequisite or optimization characteristics. However, this missing information and test results are not considered critical to their feasibility. Conversely, some concepts have a high potential score, such as the Movement and Light concepts, all of which can be justified, among other things, by the geographic location of the building, the improvements and the targeted performance objectives of the project. For the Movement concept, the main optimization characteristics that allow the achievement of 5 points are, among others:

– The Bike score (99), Walk score (98) and Transit score (80) being much higher than the minimum thresholds.
– The presence of a 103 m^2 bicycle room that can accommodate approximately 72 bicycles and is composed of several showers, changing rooms and numerous lockers, all of which are well within the minimum required limits.
– The geographical position of the building favouring walking and access to public transport.

For the Light concept, the Montreal city hall project stands out for the devices implemented to improve the brightness and luminous comfort of the workspaces. The project includes the following elements:

– Installation of motion detectors for the control of general lighting;
– Installation of dimmers in some rooms (offices and conference rooms);
– Centralization of open spaces, but installation of daylight sensors;
– Provision of an individual table lamp for each workstation or office;
– Installation of daylight detectors;
– Installation of a system of lighting control stations with customizable control buttons (programming according to action or conditional logic, e.g. time of day).

The concept of Materials and its various optimization features should be emphasized. Indeed, the characteristics of this concept are not simply limited to the quality of the materials used. This concept aims to maximize the reduction in the use of materials composed of elements harmful to health and the environment (presence of lead, mercury, asbestos, etc.), to standardize the management of these elements, to limit the use of materials containing volatile organic compounds (VOCs), to sustainably improve the policies and protocols in place regarding the choice of materials and cleaning products used, and more. In the context of upgrading to standards and heritage restoration of Montreal city hall, it is still difficult to confirm the conformity of most of the optimization features, but the potential is visible, particularly in terms of the points that could be obtained for compliance with the limits on the use of VOCs in building materials, since this criterion is just as applicable to the LEED EBOM certification already applied to the project. For example, the following elements are specified in the construction specifications: use of materials without orthophthalate, added formaldehyde or heavy metal stabilizers. It is also specified that the finish of new and restored windows and architectural caulking must meet the 250 g/L VOC limit, in addition to a required environmental product declaration. In addition, WELL's optimization features for cleaning products and maintenance protocols are equally applicable to LEED EBOM certification, as are certain criteria related to the HVAC system. Thus, supporting documentary evidence and testing must be conducted to demonstrate compliance with these characteristics specific to WELL certification, but its complementarity with LEED EBOM certification significantly increases the chances of compliance with these optimization characteristics, even at this first stage of preliminary analysis.

The second piece of information that can be drawn from Table 5 is the potential possibility of attaining a certification level higher than Silver. Indeed, the potential score identified in the detailed preliminary review of each of the optimization characteristics suggests that a score of 2 points per concept would be possible. It is possible to see in column 3 that all the concepts, with improvements, modifications and/or tests to be performed, would potentially be able to obtain the 2 points required for the WELL Gold certification level.

3.3 Adaptations Following the COVID-19 Pandemic

Over the past year, there has been an agreement to rethink the layout of workspaces in order to respect the minimum distance of 2 m at all times between each person sitting at a workstation. This decision was made through the consultation process with user representatives of the city hall, a process that has been in place since the beginning of the design phase of the project in 2017. In addition, these same workspaces have been redesigned to allow for greater flexibility and versatility, considering that, from now on, approximately 70% of the workspaces on the new floors will be open-plan with reconfigurable workstations. In addition, in order to optimize the building's air quality, the fresh air ventilation system will be decentralized without recirculation, which means that fresh air will be conveyed to each room through a separate network of ducts and 100% of the stale air will be evacuated outside the building, without mixing with the air conditioning and heating system.

4 Conclusion

Finally, LEED EBOM certification was applied to the Montreal city hall project primarily to make its operations more environmentally friendly and sustainable. In addition, the project's second objective was to demonstrate, on a city-wide scale, the feasibility of such changes to operations and maintenance policies and to demonstrate the long-term effectiveness of this certification. LEED EBOM therefore has no significant impact on the construction phase, unlike the BOMA BEST Single Building stream, Carbon Zero and Living Building Challenge certifications. These certifications focus primarily on the energy efficiency of the building, the quality and environmental performance of building materials, mechanical systems and others, which makes the certification process much more complex and initially went beyond the scope desired by the City at the beginning of the project. Over the past few years, LEED EBOM certification has evolved into revision 4.1, which has brought a number of changes, all positive and supportive of the city hall project. Indeed, this version offers performance complements in energy efficiency, user comfort, water and transportation. These changes could have had a negative impact on the project and its level of certification, but on the contrary, the LEED EBOM v4.1 version instead allowed the project to aim for a higher level of certification than expected (possibly Platinum). The additional constraints are partly addressed through the multiple modifications and improvements made by the project. In addition, LEED EBOM v4.1 allows more latitude and flexibility for projects to meet the criteria, making higher levels of certification more accessible.

Subsequently, it is possible to confirm that WELL certification would be a possible certification for Montreal city hall building considering the significant changes it is currently undergoing. By preliminarily evaluating each of the prerequisites and optimization features, Montreal city hall would be able to achieve the WELL Silver certification level, provided that all prerequisites are confirmed. Furthermore, if the City of Montreal were interested in pursuing this certification and further optimizing its potential, an opening could be envisaged to attain the Gold level of certification, while considering that changes to internal policies and programs would have to be reviewed and improved, all at a significant cost. However, it goes without saying that the achievement of such a certification for the City of Montreal would be a very important step in the field of green and sustainable buildings and in the development of municipal real estate management in Quebec.

Finally, initiatives to adapt to the Covid-19 pandemic context have been identified through the modification of workspace layouts and adjustments to HVAC systems. This is particularly important in a perspective of sustainability and adaptability of the building for the coming decades, which could be marked by more than one global health crisis.

5 Recommendations

The WELL certification is a unique certification in the field of green buildings. It is important to be aware of the fact that the WELL criteria are complex and very restrictive, including very high levels of employee benefits, a multitude of free services to be offered, a strong emphasis on the integration of nature and nutrition, and very precise thresholds for improvement in sound levels, air, water and lighting quality. As a result, not all projects are in a position to qualify for this certification and it would be recommended to opt for a feasibility analysis, offered by the International WELL Building Institute, before launching the certification process for a project.

This would limit unnecessary expenses, as the costs associated with WELL certification should not be neglected, with reference to the professionals in the certification community who were consulted. Thereafter, it would be recommended to start the WELL certification process as early as possible in building renovation or construction projects, considering the specific performance characteristics to be considered for mechanical systems, space planning, architecture, policies and programs in place.

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A New Look at Designing Electrical Construction Processes

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1 Introduction

A report by McKinsey Global Institute's Digitization Index (2017) stated that the construction industry has been exceptionally slow in adopting new tools and solutions to tackle declined productivity. The report further pointed out that smaller specialized firms such as mechanical, electrical and plumbing subcontractors usually lag in productivity [2]. However, the report suggests that an area that could enhance construction productivity, by 50–60%, is through the introduction of digital technology, new materials and advanced automation [2]. Over the past decade, data centers have been breaking ground in unprecedented numbers [11]. This rise in the construction of data center projects is expected in an era where the internet plays a critical role in our day-to-day lives. The construction of data center projects has emerged as a niche market to designers and contractors, due to the general complexity associated with these types of projects. Moreover, the construction of data centers requires extensive electrical and network cabling, and in certain situations, MEP systems may account for up to 50% of the projects value. The reality of the matter is that, for the time being, not many builders may be interested in taking on the

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S. Walbridge et al. (eds.), *Proceedings of the Canadian Society of Civil Engineering Annual Conference 2021*, Lecture Notes in Civil Engineering 247,
https://doi.org/10.1007/978-981-19-0968-9_41

risks associated with these types of projects [9, 11]. Moreover, electrical activities, especially cable pulling, are also often associated with multiple safety concerns to workers. In part, this is due to weight of cut cables, where four or five cables can weigh up to 4000 lb and can cause risks such as back injuries or strains [14].

There are several reasons why the construction industry has been slow to introduce automation technology, especially in the United States [12]. David Wisnoski, Vice President of the Industrial Systems Group based in Naperville, Illinois stated that a robot's ideal environment is a "structured" environment [12]. That being said, very few will argue that the construction industry is one that is completely controlled. Therefore, in order to achieve greater automation and robotization in the construction industry, it is essential to improve the structure of the construction environment, which requires a closer look at how tasks are accomplished and using new technologies to assist in recognizing structure [8]. Looking at the above-mentioned factors, there is a need for technologically advanced alternatives to accomplish various scopes of work in the construction industry such as mechanical, electrical and plumbing, especially on technically-advanced projects such as data centers. This study uses the cable pulling and termination process as a case study to investigate how automation can be added into a reconfigured process. It is important to consider how technology impacts processes prior to utilizing new technology in the electrical construction processes. The aim of this paper is not to replace all manual operations, but to provide support to electricians in the most physically-demanding activities and leverage their skills to operate automated devices. By mapping the existing process and proposing a future state of practice, this study provides a methodology to restructure and improve an existing electrical construction process for automation. Although this paper focuses on the electrical cable pulling and termination process, the process mapping method presented may be applicable to other key construction processes.

2 Previous Research

This study consisted of two separate literature reviews to grasp a firm understanding of the previous research conducted relating to the topic of interest. To the first review of the literature explored the various approaches that have been taken to introduce automation in the construction industry. The second review of literature identified how automation implemented in other industries can be applied to the construction industry. According to Koksela [10] the construction industry has been suffering from insufficient attention to process improvement, leading to a substantial amount of non-value adding activities in construction processes. Before introducing automation to a particular construction process, it is essential to closely assess the importance of the activities involved in that process and observe whether they add value to information and material flow. Instead of viewing automation as a tool to accomplish tasks on a job site, it should be taken as an opportunity to optimize and improve current practices. As Koksela [10] argued, the industry is still missing the principles on which a construction process could be analysed, designed, managed and improved.

Several researchers have attempted to put in place frameworks to determine the feasibility of a process for automation; however, most have failed to assess and improve the processes in place before attempting automation. For example, [8] identified three ways to assess the feasibility of a process for automation or robotization. The study looked at need-feasibility, technological feasibility and economic feasibility. According to these factors and interviews with experts from the construction industry, the researchers selected 33 construction processes as potential candidates for automation among which are drywall, pile driving, scaffolding and many more [8].

Another approach was taken by Everett and Slocum [4], where the researchers established a taxonomy for construction field operations. In this study, a construction project was divided into seven levels (1) Project; (2) Division; (3) Activity; (4) Basic Task; (5) Elemental Motion; (6) Orthopedics; and (7) Cell. The Basic Task level, which the researchers identified as a crucial level for construction automation, was broken down into a set of twelve basic tasks. The researchers argued any task performed on a construction field is comprised of one or more of the following basis tasks: connect, cover, cut, dig, finish, inspect, measure, place, plan, position, spray, and spread. These basic tasks can be performed by craftspeople or machines. Furthermore, in their study construction tasks were divided into two components: the physical components and information components. The study found that human craft workers are more productive when it comes to information intensive activities [4]. These findings reinforce the claim that the industry should re-think the way things are done by making use of its crafts people's skills in accomplishing information intensive tasks and limit their involvement in physically intensive chores that can be accomplished by robots or machines.

Agusti and Pawar [1] developed a Balanced Scorecard (BSC) to put in place evaluation criteria at operational, organizational, and societal levels to introduce automation in construction. By determining relevant Key Performance Indicators (KPIs), the BSC aids construction organizations in implementing automation in construction to "improve productivity and ensure the well-being of the environment and society". The discussed approaches used by other researchers are beneficial in looking at the big picture. However, it is essential to look at construction practices at a closer level. It is important to study existing processes before deciding on their feasibility for automation or attempting to automate their individual activities. By providing more structured processes and improved practices to accomplish construction work activities, the skills and experience of craftspeople will be put into more beneficial use on construction sites. The authors of this paper believe that automation should be used to facilitate division of labor between person and machine to utilize the best abilities of each. The aim should be to use automation to assist, rather than replace, humans and help boost productivity. This research has revealed that tasks similar to the activities involved in cable pulling and termination process have been automated in applications such as surgical operations and firefighting by using surgical assistants and robots. Some construction sites have also adopted the use of mobile robots which would be of great benefit in automating simple activities such as transporting materials around the job site.

3 Research Methodology

This paper adopted a three-step research method, as illustrated in Fig. 1. The first step consisted of conducting a state of practice to map the current cable pulling and termination process within the construction industry. The authors of the paper collected data by visiting three data center construction sites, observing the electrical crew pull cables along cable trays for one day for each site. Structured interviews were used to collect information about the most time-consuming activities and challenges the team face during this process. The authors also collected data on average durations per cable pulling activity and the respective manpower required. Four to five team members were interviewed per construction site, which included superintendents, project managers, project engineers, foremen and electricians. The authors observed the process from start to finish and recorded the activities performed for each site. The collected data was used to develop an initial process map that illustrates the sequence of activities required to complete the cable pulling process.

The second step of the three-step research method was process map validation. In this step, a panel of four industry experts were consulted to review the initial process map. Members of the industry expert panel had on average over ten years of electrical construction experience and completed over four data center projects in their careers. The panel thoroughly provided their input for developing the current process map for cable pulling. The industry experts provided minor varying sequence relating to cable pulling activities from one construction site to another; however, the larger sequence was uniform between all experts and helped in identifying the fundamental activities required to accomplish the process.

The third and final step aimed at categorizing the activities in the process map to identify waste and non-value adding activities. As explained in Fig. 2, the categorization process started by highlighting activities that have potential to be completed offsite. This can be completed utilizing several methods, including but not limited to, off site pre-fabrication. This approach would not only save labor but also the space required to store and handle bulky materials on site which will be explained in detail later in this paper. After identifying methods to complete a number of the activities

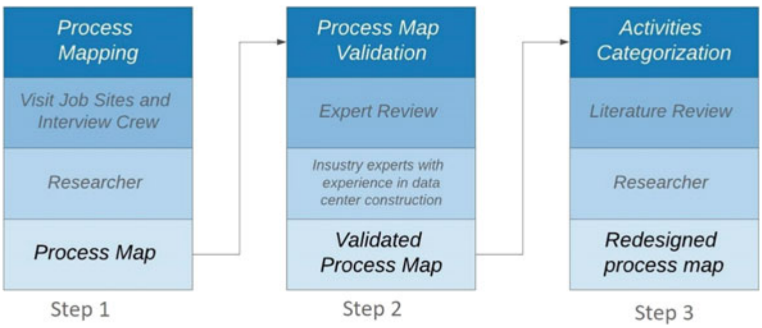

Fig. 1 Research methodology

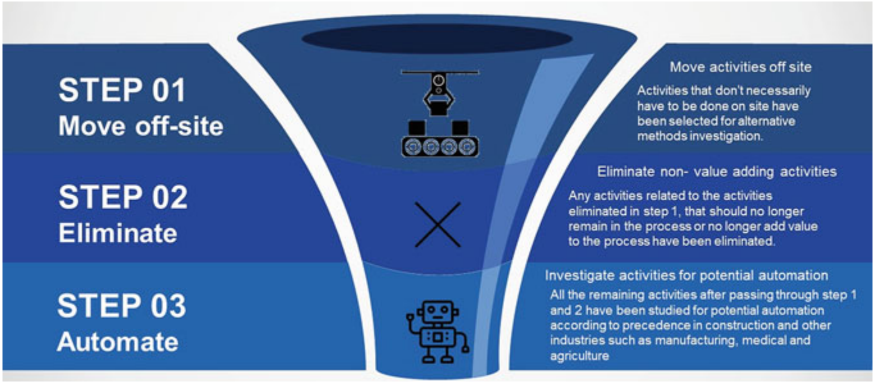

Fig. 2 Activities categorization steps

off site, certain related activities had to be eliminated from the process because they no longer fit in the overall sequence. The activities falling in the third category were studied and a literature review was conducted to identify similar activities in the construction, medical, manufacturing and agriculture industries that have successfully been automated in order to assess the applicability of automation to the these activities.

4 Current Process

For data center projects, there are two commonly used methods to run power and network pathways. Typically, the decision on which method to use is the designer's or owner's decision [7]. The first method is running overhead cables in conduits from a distribution frame to receptacles or wire busway above each cabinet. The second is running underfloor cables in a data center with a raised floor. For power cables, metal conduits are used in cases when it is required. In other cases, liquid- tight flexible cable is used. The construction of these systems requires immense coordination with other underfloor systems such as chilled water piping and fire detection (Geng, 2014). As the demand to upgrade or build new data centers continues to grow, more cabling is required to meet the increased data storage and application processing needs. The larger the size of the data center the more complex the cabling gets and the more labor it consumes.

This section aims to demonstrate the state-of-the-art process used for cable pulling and termination on construction sites after a thorough validation by industry experts. Figure 3 gives an illustration of the complex process. Arrows are used to show the flow of information and materials between team members performing different activities. The process map only shows cable pulling and termination activities during the construction phase. Several other tasks are required for completing this process

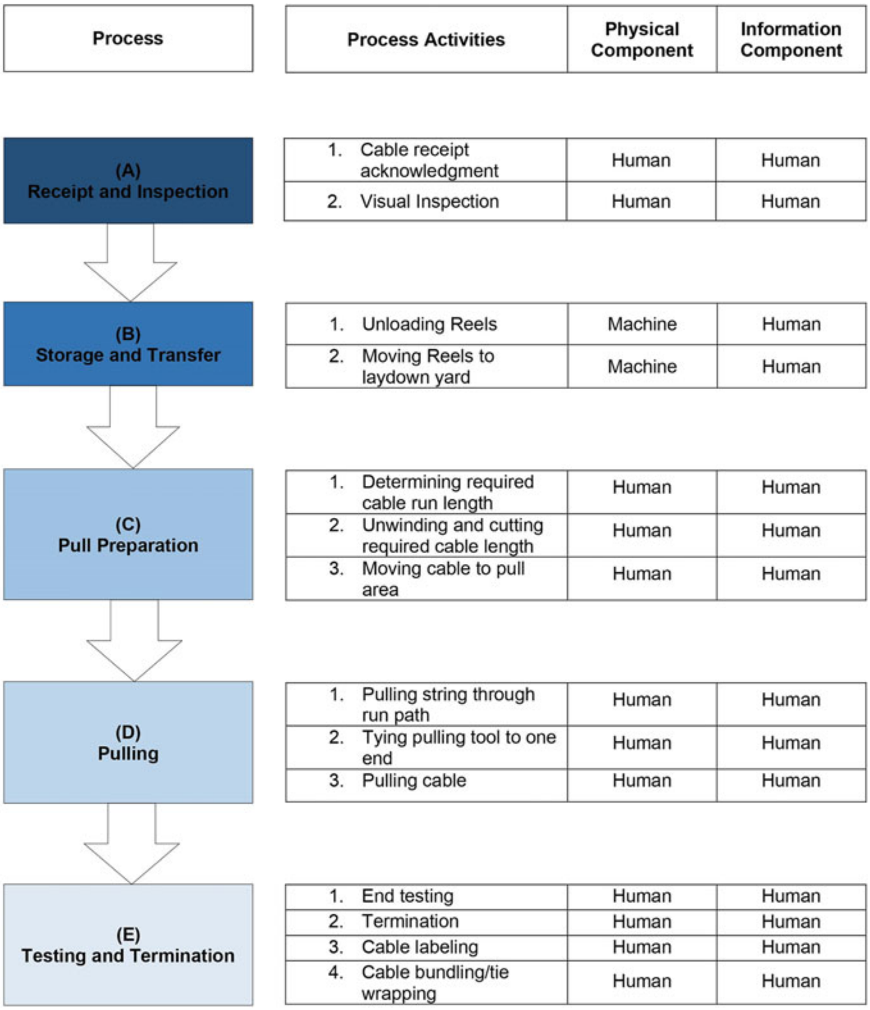

Fig. 3 Current process

before the cables arrive on site. Performing cable calculations to determine the forces required to pull cable or creating cable labels are examples of activities that are not included in the process map. Following Everett's [4] methodology, Fig. 3 illustrates the sources of physical and information components for each activity.

By observing the current practices, twelve out of fourteen activities depend on human input for both the physical and information components, the remaining two activities depend on human input in at least one of the components. Some activities involve tools or machines that provide some help to humans. Several activities are time consuming and labor intensive such as Activity C-3, moving cable from the storage area to pull area. Parts D and E, pulling cable and termination, are also labor intensive and time consuming. Depending on the size of the cable and the length of the run, it typically takes between two to six workers to pull 100 ft of cable as observed by the research team.

4.1 Rationale for Process Improvement

There are three key reasons that are in favour for restructuring the current cable pulling and termination process within the construction field. The first key reason relates to the physical injuries associated with conducting cable pulling activities. More specifically, receiving and staging the wire reels, in Part B, involve physical risks such as back strain, knees and hands crushing injuries [15]. Moreover, Activities C-3 and D-3, involve carrying cable on one's shoulders and pulling which may also cause back strain and high pulling tension recoil. The second reason is that cable pulling is a very labor-intensive process. Interviews with material handlers on data center construction sites revealed that it requires at least two construction workers to move 100 ft of medium voltage cable and at least four construction workers to pull it from its start to end point. Electricians added that an activity such as termination, Activity E-2, as mentioned by electricians on site, requires high skills, dexterity and precision; to terminate one uninterruptible power supply (UPS), it may take an electrician a day to a day and half of work.

The third reason why this process should be improved is due to its cyclic nature. The process consists of cycles of general basic tasks, and for some activities it is a single cycle that repeats over and over. In addition, most of the activities in the process are repetitive, tedious, critical to productivity and physically unsafe. Therefore, the activities involved in this process should be studied more closely by researchers. Not only may this allow researchers to create a more efficient process, but it may also allow researchers to investigate how automation can help restructuring the existing process to leverage the expertise of the industry's craftspeople. Results of such research work may support the recruitment of young craftspeople in joining the industry. Additionally, a safer work environment can be achieved through the automation of unsafe construction activities. Using conventional tools in some parts of the process, Activity C-2 and Part E in specific, is a way to reassign physical effort which means that human still supplies all the physical and information input [4]. Power tools on the other hand contribute to some of the physical input while the human operator makes decisions and directions. When it comes to automatic tools, which are used in Part B, a portion of both the physical and information component is supplied by the tool such as a forklift. However, robots have the potential to contribute with all the physical and information components of the work [4]. Some pre-programmed robots can proceed with completing tasks without any human input by making their own decisions.

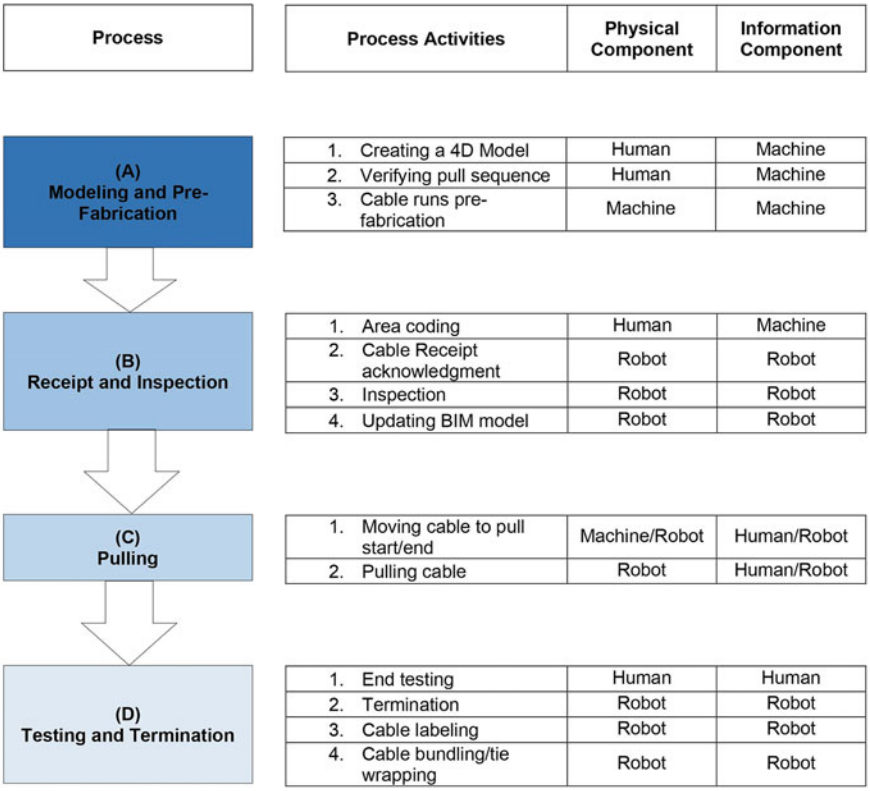

Fig. 4 Proposed process

5 Findings and Proposed Process

This section reports and discusses the key findings that were obtained through adopting the previously mentioned research method. The process improvement steps in the research methodology section were used to develop activities that make the best candidates for automation. To accomplish that, the body of knowledge relating to automation in other industries was reviewed to find proven success of automating similar tasks to the ones involved in cable puling and termination. By finding potential in automating the individual activities, the process would possibly be restructured in its entirety.

5.1 Proposed Process Brief

The proposed process, illustrated in Fig. 4, would start with the Virtual Design and Construction (VDC) team modelling the cable runs in a 4D model, using advanced software, where cable runs are linked to the project schedule. A scheduler, who creates a comprehensive project schedule where individual trade activities are arranged in a specific sequence that ties into the whole project, would be expected to revise the pulling sequence generated by the Building Information Modeling (BIM) model to verify that it ties into the overall project sequence correctly. BIM models may support the VDC team in visualizing and simulating the cable pulling process, which allows them to solve potential complex challenges in a virtual world before actual construction commences on the field [5].

The cable manufacturer, using the project specifications as guidelines to the properties and types of cable in addition to the 4D model and the cable pulling schedule, would arrange cable runs manufacture and delivery accordingly. The aim of having a 4D model is to provide the manufacturer with the following information: (1) cable run length; (2) cable run start and end point; (3) cable specifications; (4) termination type; and (5) pull date. Consequently, the cable runs would be labeled and barcoded by the manufacturer according to the project taxonomy. When pre-terminated cable arrives on site, as shown in Part B, mobile robots would potentially be of great assistance in visual inspection. They would potentially be able to directly update the BIM model and hence notify the manufacturer with any cable run rejection to arrange for re-delivery after resolving the defects. One of the recent construction innovations are robots that are equipped with stereo cameras to enable 360-degree vision and help react to obstacles and people when maneuvering around job sites. According to their manufacturer, these robots can move with a speed of up to 1.6 m/s. On a construction site, they can currently perform progress inspections and compare as-built drawings to BIM. Their high-resolution camera enables it to magnify features with 30 × optical zoom which would be useful in cable inspection in the future. In addition, these robots' ability to climb stairs, navigate through rough terrain, compare as-built drawings to BIM and its flexibility to be customized according to the user's needs, can make it a great candidate for locating areas and distributing cable runs across the job site.

However, if mobile robots or autonomous equipment would be expected to transport cable across the jobsite, in Activity C-1, then start and end points as well as area coding would be essential in aiding any autonomous equipment used on the job site to locate material drop off points. It is crucial to consider training of the craftspeople to be able to deal with the new technology. Providing workshops to convey how automation can possibly help in completing tasks more efficiently and safely will encourage the workforce to explore what this technology can offer. Adopting new technologies might also encourage younger generations to join the construction industry. It is essential to provide the workforce with the education and training that makes it comfortable with using new technology more frequently. Trainings would ideally be paired with progress monitoring and evaluation to reinforce the value of the gained skills. Crew members who prove interest and enthusiasm in adopting, testing and implementing innovative solutions to daily challenges using technology and automation, can be promoted to act as catalysts for change within their teams.

5.1.1 Pulling Cable—Snake Robots

According to the research team's site visits, pulling cable is considered a very time-consuming activity especially when a cable tray houses a lot of cable and wire. Moreover, there are some instances when there are obstacles beneath the cable trays that the worker must get through to pull the cable through the path. The process of pulling string first before the cable itself, through the run path, is an inefficient process. Pulling the string through the cable run path and then using the string to pull the cable through the same run is double work. Depending on the size of the cable, pulling cable is considered one of the most labor-intensive activities in this process. Another problem cable pullers are currently facing is the human reaction time between detecting the obstacle and notifying the pulling partner to stop pulling. In the current process, there are instances when the person pulling the cable would be standing behind a wall and cannot see the complete path of the cable, the guide in this case is usually the pulling partner's directions which are usually provided by radio. In this case the puller depends on a notification from the pulling partner to stop the pull. By the time the partner is notified to stop the pull, and reacts to the notification, the cable would be damaged already.

Snake robots are inspired from biological snakes. They are typically long, flexible and have small cross-section to length ratios to enable them to move like snakes, move over irregular terrains and in tight spaces [3]. The purpose of putting research efforts in snake robots is their potential in offering help to humans in accessing unknown and challenging environments [3]. These robots have been developed for a variety of applications including but not limited to firefighting and cardiac surgeries. A robotic system was developed to clean and inspect the cutting head of a tunnel boring machine [3]. Snake robots can be powered by electric motors, pneumatics, hydraulics and mechanical methods. After looking at the applications of snake robots in firefighting and surgery, the authors identified them as a potential facilitator in cable pulling. Such robots have the potential to be useful in pulling cable through cable trays or underneath the raised floor since these robots are equipped with contact force sensors to detect obstructions. Other snake robots are equipped with cameras that enable them to capture high quality images of steam vessels and pipes which could also be useful in capturing obstructions for faster troubleshooting. Pre-programming snake robots to run paths would be an ideal scenario in most cases. In more complicated runs, they would possibly be run by an operator similar to how drones are currently operated. So far, snake robots have been developed for inspection and maintenance applications in the field of construction. No research has been found of snake robots performing cable pulling activities, which is an area of possible future research.

5.1.2 Termination—Surgical Assistants

Termination, Part D, is a unique and challenging process because it involves more than one basic task and a high information input by human. It is not a move from point A to point B type of activity. It is rather an activity that requires experience, dexterity and precision. The two basic tasks involved in termination are cut and connect. If pre-terminated wire and cable are delivered to the job site, as proposed by the authors, then the cut part of the task no longer requires as much work, the challenge would be where to connect and how to connect. Surgical assistants would be supportive of the electrical team. They are robots that are currently used in various surgical operations. The surgical assistant acts as the surgeon's eyes and hands, which are designed to work in tight space inside the human body. During a surgery, one hand holds a lighted, high definition camera that acts as the surgeon's hands when the other hands hold the rest of the surgical tools. In this case, the robot is operated by the surgeon from the high-tech station. Surgical assistants at the operating table are responsible for observing the patient and making any necessary changes to the tools on the robotic arms [13].

Although the surgical robots are teleoperated by a human (the surgeon) that directs the robot, an apprenticeship learning approach has been proposed to extract smooth reference trajectories by recording the human guided back-driven motion of the robot [16]. This enables the robot to be programmed for several scenarios. Literature demonstrates how human behavior can be translated into patterns that can be used by robots. A mobile version of the robot would integrate tools required to connect the cables to the patch panel or servers (instead of having staplers or grippers, as required for medical applications). The robot could possibly be programmed to bundle wires together as well, since there are already existing tools for this task. Having one robot accomplish several tasks would be advantageous.

5.2 Proposed Process Improvements

The first asset of the proposed process is offering ways for division of labor between the machine/robot and human. A robot can work all the time without getting distracted or taking breaks, thus, it can reduce overall construction time. Hence, it can relieve workers from overworking themselves to meet high pressure deadlines. Moreover, meeting a construction schedule is one of the project owner's most important driving successful metrics for project completion [6]. Therefore, introducing robots and automation within construction activities may support a project team in meeting their required project completion project deadlines earlier. To further reduce the crew size required to complete the process, attempting to move part of the process off the construction site would also be a beneficial proposal. If pre-terminated, labeled cable runs are fabricated by the manufacturer, there would be no need for delivering cable reels to the jobsite. Scheduling cable runs for delivery by the manufacturer according to the project's progress schedule would save labor, space, and reduce the costs associated with labor and storage. Cable runs would ideally be delivered the night before a pull is scheduled and directly moved to the pull area to be ready for pulling the next morning. This will relieve workers from carrying the cable on their shoulder around the jobsite and will encourage using equipment such as forklifts to move the coiled length of cable directly to the pull area. This would also eliminate non-value adding activities such as unloading cable reels, moving and stage reels and the associated space and storage required would be eliminated by pre-fabrication, hence providing a more efficient process, involving less steps.

However, for this process to be adopted, several points need to be considered. First, there will be added transportation costs associated with more frequent deliveries by the manufacturer. Second, project schedules will need to be updated timely and accurately so accurate deliveries could be made by manufacturer on time and any delays would be avoided. Third, there might be some safety concerns associated with having the cable in the pull area if it is not pulled on time. Fourth, since the cables will be pre-terminated, storing extra length of cable within the cable tray or under the raised floor could be challenging. Fifth, although automating the pulling process will decrease the possibility of cable damage during pulling, if the cable gets damaged during the pull for any reason, this may possibly cause delays since cable will not be readily available on site for replacement.

6 Conclusions and Recommendations

Cable pulling and termination is one of many construction processes that requires an improvement effort. The growing demand for data centers has created a more urgent need to start analyzing processes that make up a huge scope of data centers construction work. In this paper, the current cable pulling and termination process was mapped to understand the complete picture of what is happening, then it was analyzed through several layers to determine waste and areas of possible improvement. Automation was also explored as an opportunity for improvement and was re-injected to restructure the process in its entirety. The proposed process presented a future state-of-practice that would leverage the best abilities of both humans and machines/robots. However, this is not the only possible future state, nor does it relate to all the phases involved in the cable pulling and termination process. This study focused on the roles of personnel who directly handle material; although there are also other team members, involved in the planning and management aspect of the process, such as the Designers, Site Project Managers, Superintendents and Project Engineers who play crucial roles in the completion of the process.

While the fundamental process activities should be the same across all data center construction sites, there may be some practice variations based on a firm's specific procedures or project circumstances. In addition, the specific duties of each role on a job site could be different from one electrical subcontractor to another. Furthermore, in the developed process map, the authors assumed that companies have the capabilities to employ a VDC team and perform regular and timely updates to their construction schedules. Additionally, another assumption that the proposed process has been built on is that companies will have the financial capacity to pay for automation related expenses. A limitation of this research is that it is based on visiting three construction sites. Therefore, future work may aim at collecting data from more sites, which will only further enhance the quality of the research and perhaps bring new insights to the automation process. The research methodology adopted in this study to improve the cable pulling and termination process can be applied to improve other construction processes as well. Future research can implement and test the proposed process on active data center projects. Investigating the extent to which the recommended robots can be adapted and scaled for the construction industry is also an area that requires further research. Lastly, the cost–benefit of implementing the proposed process is a scope that needs careful consideration. It is essential to understand the method of introducing these technologies in construction without making large investments that can hinder companies from taking this approach.

Acknowledgements The authors would like to thank Mortenson Construction and Corbins Electric for providing access to their jobsites and all industry experts who provided valuable input in this study.

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Framework for Automation of Construction Progress Tracking on Indoor Environment, Using Autonomous Rover and Beacon-Based System

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1 Introduction

Due to the fragmented nature of construction, its dynamic environment and unique resources, the construction industry suffers from low productivity, cost and schedule overruns, as well as recurrent safety problems. Traditional data acquisition and process monitoring remain manual, time-consuming and error prone, and yet represent an important part of construction workers' time. This explains why progress is never in concordance with the first estimations, leading to schedule delays, costs overruns and client dissatisfaction.

Recent developments in technology-based tools for real-time data acquisition could help solve these problems, and significantly improve the sector's productivity [28]. There has been much research into the use of autonomous progress tracking to deliver precise and reliable information, to the right person, at the right place and time. Such information allows the project manager to make appropriate decisions and to ensure that the project will be delivered according to the required parameters [22].

This article is a first paper of a larger research programme to develop a framework for automated progress monitoring of construction work, and to validate this framework through case studies in real contexts. The paper is composed of three parts, namely: (1) a literature review, the results of the utilization of new technologies

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S. Walbridge et al. (eds.), *Proceedings of the Canadian Society of Civil Engineering Annual Conference 2021*, Lecture Notes in Civil Engineering 247,
https://doi.org/10.1007/978-981-19-0968-9_42

in construction which are systemized in a table of technologies associations workflow; (2) a proposed theoretical framework for automated progress tracking through association of technologies and data fusion; (3) a description of a case study based on BIM, mobile Light Detection and Ranging (LiDARs) and beacon technologies, for partial validation of the proposed framework. A discussion of the results and prospects for future work will be presented at the end.

2 Literature Review

This literature review explores the automated progress tracking process in 3 steps: (1) data acquisition technologies; (2) methods for automation of progress tracking tasks; (3) systemized technologies workflow.

2.1 Data Acquisition Technologies

Combinations of three categories of technologies are reported to be used for efficient data retrieval, namely: (1) imaging data collection technologies; (2) information transfer technologies; and (3) support technologies as drones or robots.

2.1.1 Imaging Data Collection Technologies

Imaging data collection technologies, such as photogrammetry and LiDAR, allow for the capture of the as-built environment and to transform it into a point cloud. Photogrammetry is relatively easy to use in terms of data collection (pictures or video), but some factors such as lighting conditions and shadows, reflective surfaces and movement can affect the point cloud processing and the quality of the model [11, 14]. The data collection process is usually time consuming if the visual material is taken manually.

Terrestrial LiDAR provides a very dense point cloud. There are two types of terrestrial LiDARs, mobile and static. Static LiDARs provide structured point clouds which contain each scan's localization, panoramic pictures, depth map and, as a result, a complete 3D point cloud of the scanned installations. Such LiDARs are usually installed on tripods on site and capture the data in 360°. They have a good accuracy, and allow to detect all types of elements, structural components [15], Mechanical Electrical and Plumbing (MEP) equipment [6] or secondary elements [1]. They are commonly used in 3D reconstruction process, Scan vs BIM and Scan to BIM in order to compare with the as-planned BIM model [21]. Static LiDARs technology gives good results in terms of precision and density of point cloud, but the process remains manual.

Mobile LiDARs provide unstructured point clouds—with undefined localization and orientation of the separate momentary scans, and thus, do not convey the structure of the project. They capture the data in movement, and hence, the scans are less precise and less dense than a structured point cloud. Mobile LiDAR is used in the automobile industry to facilitate the autonomous navigation of cars using the SLAM algorithm. Experiments were conducted with it in a construction site context, with the purpose of reconstructing a 3D as-built model [4]. This technology is today the most autonomous way to collect data, but typically the point clouds need a lot of treatment to have good results for 3D reconstruction.

2.2 Information Transfer Technologies

Various kinds of information transfer technology can be used in the construction industry to detect the location of elements and resources in an indoor environment. In what follows, we describe the relevant specificities of Radio Frequency Identification (RFID), QR barcodes, Bluetooth Low Energy (BLE) and Ultra-Wide Band (UWB).

RFID tags can be used to support resource tracking in the supply chain during the construction process. Their possible integration with BIM was explored to track the location of all types of resources: workers, materials or equipment [28]. They can also be used for safety management by identifying high risks areas or improving emergency evacuation [19]. The RFID technology allows remote information capture and real-time tracking but can be hampered by interferences between the radio frequencies on construction site.

UWB tags, are also used to detect elements, mostly for location and tracking of equipment and resources in real-time on construction site [26]. That technology has a real-range higher than RFID and the location is more precise on indoor environments. UWB don't interfere with other radio-frequencies system. According to the literature, the signal passes through obstacles, which gives high accuracy positioning on construction site [3].

Another possibility is the QR barcodes code which can be used to detect element's location. The codes are fixed on elements and read by a portable light scanner or any mobile camera-equipped device [23]. That technology is of a relatively low interest for construction because of the low durability of the labels and their very short range.

The last technology explored for indoor object detection is the BLE. In construction the BLE beacons are used to detect and to track tools [5], or equipment on the site map [24]. They can also help for the safety management on site [27], as they can assist in detecting hazardous locations in relation to workers' proximity to them [25]. Recently, BLE is also explored for productivity management in prefabrication by using them to remotely control the machines [12]. Finally, for collecting data for production control, a real-time tracking system was developed, attaching BLE beacons to the workers [2]. The benefits of that technology are the low price of the beacons, and a very-user friendly interface. Beacons can be read and updated by all mobile BLE-equipped devices as smartphone and tablets. However, their range is shorter than RFID or UWB.

More indoor positioning systems can be explored, such as Infrared (IR), Ultrasonic, Zigbee or Wireless LAN [3] but they are rarely used on construction sites. We can also mention the Global Positioning System (GPS) and Geographic Information System (GIS), very useful in construction but they are not in the scope of our research because they only work on outdoor environments.

2.2.1 Supporting Technologies

"Support technologies" are defined as technologies which are not literally capturing data, but which can be combined as a support for data acquisition technologies. Traditionally, data acquisition is done manually by workers who take pictures or use fixed stations (tripods) for LiDAR for example. Any mobile vehicles can be combined with acquisition technologies, but recently, two types of autonomous technologies adapted for construction industry appeared on the market, the drones or Unmanned Aerial Vehicle (UAV) and the Terrestrial Robots or Unmanned Ground Vehicle (UGV).

UAV are more and more used and investigated for construction management tasks [17], for tracking resources locations [16], or to perform inspection for quality, safety and maintenance and to compare the acquisition with the 4D model [20]. The utilization of drones on indoor environment had made impressive progress but it still very challenging due to the low flight reliability of small UAV. According to [8] this is the reason why drones are not used for indoor construction sites yet.

A UGV robot is a small vehicle that can browse the construction site to capture different data on the field—following a predefined path, remotely piloted by a user, or in an autonomous manner. In construction, robots are used for automation of different tasks, such as: site and material resources management, workers' safety and for creation of an as-built 3D model through laser scanning or photogrammetry [4]. Limitations are in respect to the battery lifetime and in the robot's ability to move in rough environment (use stairs, cross or avoid obstacles). Rovers are well adapted for indoor environment, because they don't need satellite information, and all the mapping process can be implemented inside the robotic navigation system from the BIM information, and complemented by the SLAM algorithm.

2.2.2 Automated Progress Tracking Through Association of Technologies

In the previous parts of this paper, research on individual data-acquisition technologies was explored—presenting their benefits and their limitations. Combining these technologies has the potential to successfully address some of the problems mentioned in the introduction of the paper. Thus, some hybrid systems are also presented in the literature. For instance, the association of static LiDAR and photogrammetry is used to manage the progress of work and to improve the quality of the information [11, 20]. The combination of UAV or UGV with laser scanner or beacon reader allows to cover a higher perimeter on site, and to explore difficult areas in order to acquire data quickly and safely [29]. Other researchers explore the association of beacons technologies with GPS to add location characteristics to the tagged items [30].

In what follows, we describe the steps necessary for automated progress tracking on construction site.

2.2.3 Data Retrieval

Imaging data—point clouds, images or videos captured by LiDAR, represents directly the reality and provide useful information from the construction site. For beacons data, the process requires more effort as that type of data does not show directly interpretable information for the progress tracking. It must be sorted, classified and analysed to register useful information. The captured data from beacons is a unique ID and the associated information. To be used it has to be stored in a database in which information can be associated and modified. The link to the BIM can be created by using a database which contains the beacon information [27]. However, it could be more complicated and manual for different types of information. After this, the information is sorted and filtered for the needs of the next step.

2.2.4 Data Treatment

The data treatment represents the necessary processing to extract usable information from the data acquisition. The treatment of the point cloud is a complex process which differs according to the type of point cloud. For a structured point cloud, after noise reduction, in various software it is possible to create a mesh model, which will allow the detection of elements and the generation of an as-built 3D model. The process is much more complex for unstructured point cloud. To generate a 3D point cloud from the camera data, a Structure from Motion Technique is used. The point clouds from the mobile LiDARs are created by the SLAM algorithm also used by the robot navigation. Information from this technology is less precise than a structured point cloud and it has to undergo additional processing. A Statistical Outlier Removal (SOR) algorithm is applied to reduce the noise: it deletes points without a selected number of neighbors. Once, this filtration methods used, it is necessary to merge the points clouds to create a unique point cloud with all the information. It is generated by the (Iterative Closest Point) ICP algorithm which allows the alignment of the multi-source point clouds. Obtaining a single point cloud is necessary for the process of semantic segmentation achievable through Machine Learning and Computer Vision methods, leading to elements' identification [4].

2.2.5 Progress Estimation

Then, the step of progress estimation is based on data analysis and consists in the comparison between work done and work planned for the same date. That is why, in the larger context of this research we outline the need to build a reliable as-built 4D model allowing the comparison with the as-planned. The as-built model is superposed on the as-planned for comparison and to underline deviations—which represent delay or advance in the work. The next step in the process is object recognition and the correspondence between object detected and expected. For this stage, many authors offer methods and procedures. The recognition can be done by creating mesh model and comparing the geometry of elements by their size. This method works for different types of elements such as structural elements [4, 14] or MEP equipment [9]. The number of similar points between the two models also allows to detect the elements [7]. Other methods are the recognition by materials texture [10] by the color of elements [1] or also by the extraction of quantity to estimate the progress [18].

2.2.6 Data Communication/Visualisation

Finally, the last step of the progress tracking process is the choice of the communication—usually through visualization, wished by the project manager. For this task, Augmented Reality/Virtual Reality (AR/VR) are more and more proposed because it facilitates the understanding and the communication of the results between all actors and allows to see clearly the deviation or the advancement of the works by using color-code [14]. In addition to AR, we can imagine other methods of visualizing progress, such as a dashboard with key progress figures (percentage of work completed, percentage of work ahead, on time, and behind schedule, costs incurred, remaining budget, etc.) or a 4D colored model with resources installed and recently validated, those awaiting validation, or those in stock [13].

2.2.7 Systemized Technologies Workflow

Many of the previously reviewed technologies have to be combined or linked in order to automate the data acquisition and treatment. The following diagram (Fig. 1) represents the consecutive steps of technologies' combinations found in the literature review, in the process of construction progress tracking.

It should be mentioned that the technologies, their links, combinations and the processing of the data, presented in the above diagram, do not exhaustively describe the domain but only give a snapshot of the findings in the literature review of this paper. The figure proposes a framework for the representation and the actual content can be periodically updated to follow the evolution of the technologies and methods.

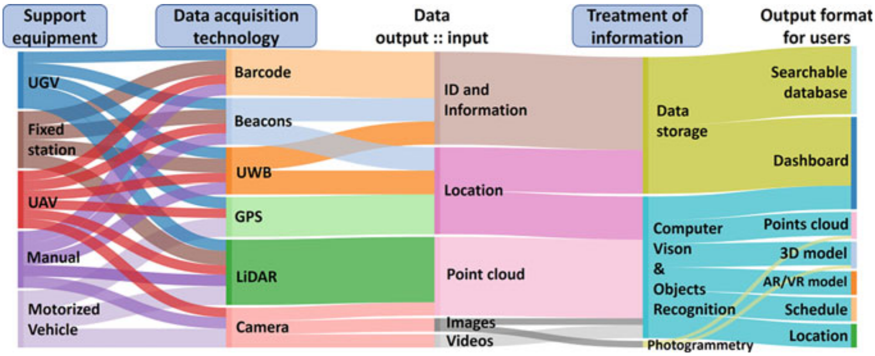

Fig. 1 Exploration of technologies associations for progress tracking

3 Proposed Framework

Based on the literature review, a general framework for construction project progress monitoring was designed. As shown on Fig. 2, the data acquisition process is separated in three parts depending on the type of data that needs to be acquired, the necessary precision and the ability of technologies. As presented on the figure: in red is the process of acquiring outdoor data needed for topographic surveying, excavation or outside monitoring. This acquisition is usually supported by GPS-guided UAVs

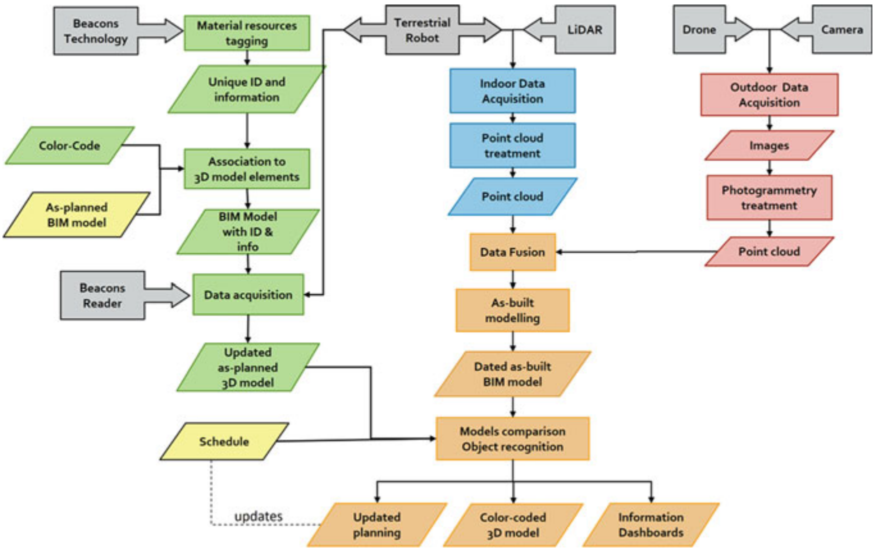

Fig. 2 Operational framework for holistic automatic progress tracking system

equipped with camera and LiDARs, to obtain a point cloud of the exterior conditions; In blue is the process for acquiring indoor data—mainly of architectural and structural elements. There the trajectory and the data capture need to be more accurate. This acquisition can be supported by a LiDAR-equipped autonomous terrestrial robot, which is browsing on the field scanning the as-built reality and providing a 3D model of the inside environment; Finally, in green is a process aiming at identifying smaller objects and data which is difficult to capture with the first two acquisition methods. This acquisition is achieved by using beacon technology. After processing and data-merging, the collected data allows for the automatic update of a partial 3D model. At a further stage, all output data (3D models) is merged to create a usable and reliable 4D as-built model that can be compared with the as-planned BIM model. Following the different methods for object recognition, this comparison highlights the differences between the two models and provides information for the progress of the works. The output data of the process can be an updated schedule, an updated 3D model using color-code to visualize progress, or a dashboard providing the key indicators required by the project manager. This operational framework for automated progress tracking is conceived as a tool for helping project managers make good decisions about data acquisition for the purposes of project progress tracking.

4 Development of the Indoor Data Acquisition System

A case study was designed to partially implement the above presented framework and explore with more detail the indoor data acquisition system. This automatic progress tracking scheme runs through four processes: (1) transmission of the field data by the autonomous rover equipped with LiDARs, cameras and beacon reader, (2) LiDAR data acquisition process, (3) Beacons-based data acquisition, and (4) data treatment process including integration with the BIM.

4.1 Transmission of the Field Data

The data collection of the site resources is supported by an autonomous terrestrial robot equipped with mobile LiDARs, cameras and a beacon remote reader. With the Robot Operating System (ROS) it is possible to collect point clouds directly from the LiDARs and the cameras with a mapping system based on the SLAM algorithm approach, also used for the autonomous navigation. When the robot follows a predefined path, the reader positioned above is continuously sending signals in all directions. When beacons are at a range <50 m from the robot, they send their ID (and other) information to the reader as a response to its impulses. The data from all beacons is momentarily stored in the robot during the acquisition. The robot's position during the acquisition is known, so it is possible to calculate the location of the resources (using an algorithm developed specifically for this purpose). In order to reduce the size of the acquired data, we can calibrate the signal retrieval to one scan every 30 s, for example. Then, when a Wifi connexion is available, all the data can be sent to a database. The data from previous acquisitions is replaced by the new one to update the database with the new position of the resources. By limiting the manual data collection, the data acquisition process is believed to become more efficient in terms of speed, quality (less errors), safety and productivity, while the workers can be assigned to other value creating activities.

4.2 LiDAR-Based Process

This process consists in retrieving and processing the data captured by the technologies used for the autonomous navigation of the Rover, namely mobile LiDARs and moving cameras. Different point clouds are registered on site, one from each technology. The point clouds from mobile LiDARs contain only geometrical information but the ones from cameras also have RGB information. First, the acquired data sets are pre-processed individually to improve the quality using noise reduction or applying clusters to remove distant points. Next, the different point clouds are registered together using algorithms in order to create a unique point cloud of the as-built with more information. In order to detect elements in the point cloud, a segmentation is applied with Machine Learning techniques. Some specific datasets are used to detect indoor elements of the point cloud with their plans, common geometry or RGB information. Next, the elements are labeled and colored by type, and thus, can be isolated by types of elements in order to be compared with the objects from the BIM model.

4.3 Beacons-Based Process

This step of the system starts by allocating information to the material resources that should be monitored, by attaching beacons to the relevant elements with the purpose of providing a unique identification (ID) for each of them, to link information to these IDs, and thus, to the resource. A variety of information can also be added—the name of the product, the manufacturer, the dimensions, installations instruction, the delivery date, etc. All the functioning of the system is based on the rewritable nature of the chosen technology. Two technologies could support this kind of use: RFID technology and BLE Beacons, because both are composed of rewritable tags and have enough long-range readers to collect remotely and wirelessly the field data.

The "progress status" of the resources is calculated with the information of the resource location. Indeed, thanks to the BIM model, the expected position of each resource is known. The beacon reader exports the location information of the beacons by knowing the position of each scan by the robot. These positions are compared with the position expected from the BIM in the server database. For instance, when

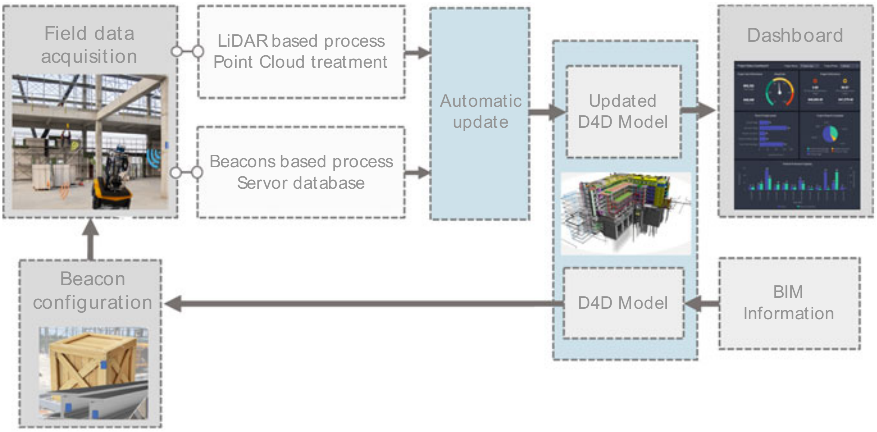

Fig. 3 Overview of the developed beacon- and LiDAR-based system for job progress tracking

the resource is detected by the scanner in the storage area, the status is "Stocked"; if it's close to the expected installed position, the status is updated into "Misplaced"; and if it corresponds to the installed position as-per the BIM, the status will be "Installed". To allow for updating of the resource's information, a specific application is developed and installed on the field mobile devices (e.g. smartphones or tablets). The interface compares by ID the position scanned with the position expected and can show the status to the user. It can also provide a progress status of all the elements by calculating the percentage of installed items (Fig. 3).

4.4 Data Treatment for Automatic Update Related to the BIM

This part presents step-by-step the process of automated progress tracking and connecting it to the BIM model. To facilitate the process, it is recommended to scan the construction site floor by floor. First, it is required to prepare a Dated 4D (D4D) model, which facilitates the interpretation by removing elements that are not expected to be present at this time of the construction. For instance, it is advised to export the D4D model of the data acquisition day. Once the D4D model is prepared, a Dynamo script is developed to extract a certain type of elements on a selected floor. The position of the elements (x,y,z) and their unique ID are exported into an Excel or a.csv file which can be imported into the database. Thanks to this script, we can also configure the beacons with the Revit ID corresponding to the elements and find their expected position on the server database. Furthermore, that extraction by type of element allows to create a mesh model with the elements concerned. This mesh can be registered and compared with the "segmented by elements point cloud" (Sect. 4.1) with a point-to-point deviation method. Thus, the elements from the point clouds can be detected as well-positioned or not.

The beacons' data (ID, x,y,z position) captured and used for updating the database (as explained in Sect. 4.2), allows the system to update automatically the 3D model (in Revit) by comparing to the database. The scanned positions are compared with the expected position from the first script and the progress status is indicated. The unique Revit ID is attributed to the beacons attached to the corresponding material resources. This link allows to configure by coding the interaction between the database and the BIM model. A color-code following the "progress status" from the database is established to support the visualization of the progress in the model. For instance, the resources with the "Installed" progress status appear in green in the model, the "misplaced" in red, and those which are stored or in delivery do not appear yet. With another script, the color-code can be applied on the D4D model from the information into the database, and the elements will reflect the status of the elements in it. So, with each acquisition, the database and the D4D Revit model are updated reflecting the progress of the installation on site.

5 Case Study

In the case study designed for the partial validation of the proposed framework, the data acquisition is supported by a Clearpath Jackal rover. The following equipment has been mounted on it (some of it only for test purposes): two Ouster LiDARs (one to capture data around the rover, the other—above); a Velodyne LiDAR; and three Intel RealSense RGB cameras. With this system, different points clouds were captured on several construction sites: in a hospital, a university and a warehouse.

The acquired point clouds were processed to improve the quality in order to be segmented by elements. To perform the semantic segmentation, we used Machine Learning datasets and Computer Vision to recognize the elements. Given the low density of the point clouds from the mobile LiDARs and the large amount of 'noise' from the cameras with RGB information, the data was difficult to exploit. Many elements could not be recognized by typical semantic segmentation algorithm. To improve the quality of the mobile LiDARs point cloud, we used the BIM model as a patch to have an as-built point cloud corresponding to the field with better density and accuracy. Using the SLAM point clouds, we found that it is possible to detect structural elements (structural columns, walls, ceilings, floors). The objective for the next iteration is to apply a filter during the registration process of the RGB-mapped point cloud and to have a usable and less noisy point cloud, allowing for the detection of more types of elements.

The beacons-based experiment was carried out in a university building, using BLE Beacons (Confidex Viking model). The beacons remote reader was an Android smartphone equipped with the configuration app for beacons and a BLE scanner app. Using a Dynamo script, the BLE beacons are configured with the ID of the corresponding BIM element. For the purposes of this case study, the beacons were manually placed on different elements inside the building, scans were done from different positions with the smartphone as a reader and the data was manually exported into an Excel file to compare with the real data from the BIM model. This test was realized to calculate the accuracy of the beacons to determine if they can be used with relatively small and closely positioned elements (typically MEP or specialized equipment). The results from the beacons showed a large percentage of error between the distance estimated by the reader and the real distance known from the BIM model. The beacons were well detected and with the correct information from the configuration, but the position calculated by the reader was far from the reality. This was due to the presence of many metal obstacles which interfere with the signals emitted by the BLE beacons. The option to detect the exact position of the object and to determine if it is well placed is not applicable with that type of beacons. In the next stage of our research we will apply that beacon system methods on construction site with a more complex UWB-beacons based system, (Pozyx) to detect the elements.

With these two types of data—point cloud from a mobile LiDAR and data from beacons, we creates an as-built model, which was compared to the as-planned D4D model (in Navisworks or BIM360). We get a colored model with expected and unexpected elements and we can export a list of selected elements and their properties to compare and estimate the progress.

6 Discussion and Future Works

This paper proposes an operational framework of technologies and their associations for automating construction progress tracking. However, the implementation and the deployment of the entire framework from the data acquisition to the dashboard remains theoretical. Some of the methods are well known today, such as autonomous robot navigation or the comparison of structured point cloud with the BIM model. However, others are still to be developed, such as the comparison between unstructured point clouds with the BIM model, the development of a D4D model or a precise indoor location system. More research is planned to be done concerning the following steps of the framework: (1) improving the registration of point clouds from moving cameras—to be able to perform a semantic segmentation method; (2) development of a D4D model—to extract information of elements which are required to be compared; (3) development of an automatic system to compare the segmented point cloud with that D4D model.

Concerning the beacon-based system, it has been proven that the BLE cannot give the exact position of an element, so other indoor location system will be explored such as UWB to detect the precise location. The configuration of the tags remains semi-manual, while their placement and configuration should be done in the fabrication facilities for optimal efficiency. Moreover, work has to be done to automate transmission of the data from the beacon reader to the database, making it be possible to automatically update the status information in the Revit model.

In the current research project, we made a deliberate choice to explore mobile acquisition systems, rather than the static terrestrial system, already tested on construction site such as Leica BLK 360, Trimble SX10 and others. This explains the difficulties to obtain good quality results with technologies which are not initially conceived for that use. Future research is planned to explore their potential for the construction site.

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Parallelization Strategies for Hierarchical Density-Based Clustering Algorithm Using OpenMP for Scan-To-BIM Applications

J. Ma and F. Leite

1 Introduction

Scan-to-BIM is an active research field in the civil engineering domain [3, 11, 13]. The main objective of this topic is to create an as-built 3D model through computerized processes leveraging 3D imagery either via 2D high-resolution images or 3D point clouds, which can be leveraged to support developing a digital twin of an existing infrastructure/facility. Scan-to-BIM consists of three stages: (1) achieving the "as-is" dataset from a real-world environment using scanning devices, (2) segmenting the dataset and classifying each segment per object category, and (3) developing digital "as-is" condition of the scene using 3D modeling software. Prior to the modeling phase, the achieved 3D dataset, generally 3D point clouds, contains geometrical information and a set of points can be segmented based on their feature similarities. For example, the points formed on the same planar region (e.g., wall, floor, and ceiling) would have similar normal values that are densely located together in a vector space. The objects with complex geometries (e.g., curvilinear objects) such as mechanical, electrical, and piping systems are not as easily grouped using only the geometrical features; however, deploying high-dimensional features including color and normal vector information could ease the segmentation process.

As an unsupervised learning method, clustering methods can be utilized for segmentation which provides insights from the dataset through investigating unknown structures in a dataset without exploiting any ground truth target information. Although there are numerous types of clustering algorithms, none of them can precisely define the notion of a "cluster" [10]. Hence, new algorithms are still being

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S. Walbridge et al. (eds.), *Proceedings of the Canadian Society of Civil Engineering Annual Conference 2021*, Lecture Notes in Civil Engineering 247,
https://doi.org/10.1007/978-981-19-0968-9_43

developed and compared to find the one with the best fit for to a given dataset. Meanwhile, Density-Based Spatial Clustering of Applications with Noise (DBSCAN) [9] has been proven to show effective segmentation performance in the context of the 3D points generated for indoor building environments [1, 7, 8, 19]. However, the performance of DBSCAN is highly variational depending on the user-defined parameter set (i.e., $\in$ and $minPts$) and manual optimization is necessarily required. Latterly, to mitigate this problem, DBSCAN developers proposed Hierarchical Density-Based Spatial Clustering of Applications with Noise (HDBSCAN) [4–6] which automatically produces an optimal solution from all possible DBSCAN solutions in a hierarchical manner. HDBSCAN possesses distinct advantages over other clustering algorithms: (1) avoids "flat" (i.e. non-hierarchical) labeling of data objects, (2) automatically simplifies the hierarchy into the most significant clusters, and (3) requires a single input parameter (i.e. minimum number of points) for density threshold.

However, this algorithm has an overall computation time complexity represented as a quadratic form (i.e., $O(dn^2)$) and 3D point clouds generated from the laser scanner are massive in terms of data size. Moreover, they are generally downsized to avoid memory exceeding problem [16]. Thus, in order to fully exploit the advantages of HDBSCAN on large-size point clouds dataset, it is essential to evoke the concept of parallelism for effectively processing the dataset. In accordance with the needs, this study aims to parallelize major time-consuming components of HDBSCAN algorithm using OpenMP programming interface for thread parallelization. Parallel efficiency was measured by calculating speedup and efficiency from strong and weak scaling results.

2 HDBSCAN Procedure and Complexity

Prior to giving explanations on the parallelization strategy, here are keywords to be introduced in advance: (1) Core Distance ($d_{core}(x_p)$): the distance from an object to its m_{pts}-nearest neighbor, (2) Mutual Reachability Distance $d_{mreach}(x_p, \ x_q) = \max(d_{core}(x_p), d_{core}(x_q), d(x_p, x_q))$: the maximum distance of two core distances of x_p and x_q and the distance between two objects, and (3) Mutual Reachability Graph (MRG) ($G_{m_{pts}}$): a complete graph in which the objects in the entire dataset are vertices and the weight of each edge being the mutual reachability distance between the respective pair of objects [5]. A sequential HDBSCAN algorithm consists of four main steps as shown in Table 1.

Table 1 HDBSCAN main procedure

Input : Dataset X (row : sample, col : attribute), Parameter m_{pts}
Output : HDBSCAN hierarchy

1. Given a dataset X, compute the core distances of all the data objects, and compute MRG, $G_{m_{pts}}$
2. Compute a MST of the MRG, $G_{m_{pts}}$
3. Extend the MST to obtain MST_{ext}, by adding for each vertex a "self-edge" with the core distance of the corresponding object as weight

The computational complexity of step 1 is $O(dn^2)$ where n is the number of objects and d is the dimensionality of the data objects. Step 2 requires to construct a Minimum Spanning Tree (MST) which can be computed in O(E + VlogV) with Prim's algorithm [14] using Fibonacci Heaps [17]. If using complete graph, as in this study, the number of edges is $\frac{n(n-1)}{2}$ which leads to a $O(n^2)$ complexity. Step 3 requires an addition of n self-edges where the complexity is O(n). Lastly, step 4 can be computed in $O(nlogn)$ which needs sorting of the edges. Thus, the overall computational time complexity is $O(dn^2)$. This study focused on parallelizing steps 1 and 2 which are the major time-consuming steps for the HDBSCAN algorithm.

3 Parallelization Strategy

In this study, the input dataset is initialized to have three dimensions with random values to simulate large size point clouds. For step 1, normalization with finding the maximum and minimum number and calculating a distance matrix were parallelized and the merge sort algorithm was parallelized by using the 'sections' and 'task' constructs. For step 2, customized reduction and Compare and Swap (CAS) strategies were utilized for parallelizing Prim's algorithm.

3.1 Step 1 Parallelization

Step 1 of HDBSCAN requires computing MRG from a given dataset. When implementing HDBSCAN in practice, it requires further detailed steps including normalization of the dimensions to have values in common scale into the range 0 ~ 1, computing distances (e.g., Euclidean distance) for each pair of objects to generate the core distance matrix, and generating MRG.

Normalization requires the minimum and maximum values of each column. For parallelizing this procedure, this study adopted data parallelism through work-sharing construct (i.e., #pragma omp parallel for) where the data is divided into blocks for the threads that each thread finds the minimum and maximum values of each block. Reduction clause was used to summarize the partial results. The pseudocode is shown in Table 2. This step is perfectly parallelized showing the complexity O(n/p), where the problem remains same and no communication occurs between the threads. Here, n and p denote the number of operations and processors, respectively.

Distance matrix can be computed naively by calculating the distances for all pairs of rows in the dataset, which takes $O(n^2)$ complexity. However, since the distance matrix is symmetrical, the code was formed to calculate distance only once for each pair of rows. Using the same logic as the normalization process, it was parallelized by making each thread to calculate the distances for certain rows which has the size of the number of total rows divided by the number of threads. In this process, however, each thread has varying computational works since the number of rows

Table 2 Normalization pseudocode

```
Input : Array, column size (col), row size (row)
Output : Normalized array

1. Compute minimum and maximum values per column
Minimum value per column ← 0, Maximum value per column ← ∞
for column c = 1 … col do
    #pragma omp parallel
        #pragma omp for reduction(Minimum value) reduction(Maximum value)
        for row r = 1 … row do
            // Loop through the rows per thread to find the minimum and maximum values
        end
2. Normalize the array per column
        #pragma omp for
        for row r = 1 … row do
            // Loop through the rows per thread for normalization
        end
end
```

that have to be considered for calculation decreases as increasing the row index. To handle this irregular computation per iteration, dynamic scheduling was performed in a 'first come, first served' basis. The complexity of this process is $O(n^2/p)$ and the pseudocode is shown in Table 3.

The next process is to compute the MRG from the core distance matrix. This step requires sorting distances for each row to find the distance of m_{pts}-nearest point. As a baseline, the merge sort algorithm using 'sections' construct was adopted from the open source code hosting platform GitHub (https://github.com/avcourt/hybrid-programming/). A sequential merge sort algorithm is shown in Table 4.

Table 3 Distance matrix computation pseudocode

```
Input : Array (arr), column size (col), row size (row)
Output : Distance vector

#pragma omp parallel for schedule(dynamic)
for row_1 = 1 … row do
    for row_2 = row_1 … row do
        for col = 1 … col do
        // Loop through the columns to compute pair-wise distance
        end
    end
end
```

Table 4 Sequential merge sort pseudocode

```
Input : Array (arr), merge limit size (merge_lim)
Output : Sorted array (arr)

Seq_mergesort (arr, size, temp) // temporary array to copy the elements

1. If (size < merge_lim)
       Insertion sort (arr, size);
2. Seq_mergesort (arr[0:n/2], n/2, temp)
3. Seq_mergesort (arr[n/2:], n-n/2, temp)
4. Merge (arr, size, temp)
```

The sequential algorithm consists of recursive functions for divide-and-conquer and merge operations. Prior to the release of OpenMP 3.0, the 'sections' construct has been widely adopted for parallelizing recursive algorithms. The 'sections' is a work-sharing construct that contains a set of structured blocks that are to be distributed among and executed by the threads in a team. This construct is typically utilized with nested parallelism which enables the creation of a team of multiple threads inside the recursive loops. However, creating excessive parallel regions causes extra synchronization due to its implicit barrier at the end of the construct, and thus, nesting parallel regions is susceptible to oversubscribing the system (i.e., creating too many threads over the available CPUs) which causes significant performance degradation. As an alternative to 'sections', the 'task' construct can be used which was introduced in OpenMP 3.0 to support solving primarily irregular problems such as while loops where iteration limits are not known at compiler time (i.e., unbounded loops) and/or recursive algorithms that solve divide-and-conquer problems. When executing the 'task' construct, each encountering thread creates tasks, and a team of threads is created that each thread is assigned to one of the tasks generated to complete. Major benefits of using tasks come from the fact that unlike 'sections' blocking at the end of the directive, tasks queue up and execute whenever possible and tasks do not require the use of nested parallelism which can avoid oversubscription problems. In this study, experiments were made to compare the performances of 'sections' and 'task', and the parallelized pseudocodes are shown in Tables 5 and 6. Radenski [15] has shown the method using 'sections' to parallelize recursive functions without making significant changes to divide-and-conquer methods. In this case, a single thread is responsible for each parallel section and assigning section for each recursive function enabled dividing total works by number of available threads by concurrent executions. Following the same structure, 'sections' constructs were replaced with 'task' where the 'taskwait' clause was included to act as an implied barrier to ensure synchronization.

The main objective of step 2 of HDBSCAN is to construct MST from MRG. Historically, there exist three popular MST algorithms: (1) Boruvka [2], (2) Prim [14], and (3) Kruskal [12]. The basic form of these algorithms shows same complexity

Table 5 Parallel merge sort using 'sections'

```
Input : Array (arr)
Output : Sorted array (arr)

Par_mergesort (arr, size, temp, threads) // temporary array to copy the elements

1. If (threads == 1)
        Seq_mergesort (arr, size, temp)
   else (threads > 1)
   #pragma omp parallel sections{
        #pragma omp section
            Par_mergesort (arr, size/2, temp, threads/2)
        #pragma omp section
            Par_mergesort (arr + size/2, size – size/2, temp + size/2, threads - threads/2)}
   end
2. Merge (arr, size, temp)
```

Table 6 Parallel merge sort using 'task'

```
Input : Array (arr)
Output : Sorted array (arr)

Par_mergesort (arr, size, temp, threads) // temporary array to copy the elements

1. If (threads == 1)
        Seq_mergesort (arr, size, temp)
   else (threads > 1)
   #pragma omp parallel{
   #pragma omp single nowait
        #pragma omp task
            Par_mergesort (arr, size/2, temp, threads/2)
        #pragma omp task
            Par_mergesort (arr + size/2, size - size/2, temp + size/2, threads - threads/2)}
   #pragma omp taskwait
2.      Merge (arr, size, temp)
```

Table 7 Pseudocode for the customized reduction function

```
Input : Key values (key_values), mstSet (mstSet), Number of vertices (V)
Output : Index of the minimum value (min_index)

MinKey_reduction (key_values, mstSet, V)
Declare the reduction clause for the struct containing two variables of minimum value and index
Initialize struct, local_min, local_min_index

#pragma omp parallel for reduction (min: struct)
    for v = 1 … V do
        If (v not in mstSet) and (key_values[v] < local_min (per thread))
            local_min = key_values[v]
            local_min_index = v
```

of O(ElogV) where E is the number of edges and V is the number of vertices. This study adopted parallelism for two major parts in Prim's algorithm. The first part is to loop over all vertices and find a vertex which has a minimum key value. Two parallelization strategies were compared for this step. Firstly, a user-defined reduction function was constructed for retrieving the index of the minimum key value across multiple threads (Table 7), and the CAS concept was utilized which avoids multiple threads from accessing shared memory (e.g., minimum key variable) simultaneously (i.e., race conditions) through parallel primitive (i.e., priority write) [18, 20] (Table 8). The second part requires updating parent and distance values based on previously selected vertex. Compared to the first part, this procedure does not raise race condition when looping over all vertices using multiple threads. Thus, 'parallel for' function was utilized as in Step 1. The total work and depth complexity of the parallelized version are the as same as the sequential one while the lower bound of time complexity is decreased to $O\left(\frac{E}{p}\log V\right)$.

Table 8 Pseudocode for the CAS

```
Input : Key values (key_values), mstSet (mstSet), Number of vertices (V)
Output : Index of the minimum value (min_index)

MinKey_CAS (key_values, mstSet, V)
Initialize the atomic variables (global_min and global_min_index) that keep the global minimum value
(and its index) found across the threads
Initialize local_min

#pragma omp parallel for{
   for v = 1 … V do
      local_min=global_min // Update local_min with global_min
      while (v not in mstSet) and (key_values[v] < local_min)
         if CAS (global_min, local_min, key_values[v]) == False // If global_min is updated by other
                                                     threads with lower value at this point
            local_min=global_min // Update local_min with global_min
         else // If the global_min is not updated by other threads at this point and has same value with
               local_min

            global_min = key_values[v], global_min_index = v
            break
```

4 Experimental Setup

This study utilizes OpenMP for parallelization using C/C ++ codes on the Stampede 2 supercomputer at the Texas Advanced Computing Center (TACC). AVX-512 instructions were set for the compiler and Non-Uniform Memory Access (NUMA) policy was configured to optimize the memory access from the threads. Performances of four cases were evaluated by implementing strong and weak scaling measurements by increasing the number of threads from 1 to 48. Speedup and Efficiency were calculated for representing strong and weak scaling results, respectively. Data size (i.e., array size) for each experiment is displayed in the figure.

5 Results and Discussions

This project implemented parallelization in a total of four algorithms: (1) Normalization, (2) Calculate distance matrix, (3) Merge sort, and (4) Prim. Strong and weak scaling performances of each algorithm are visualized in Figs. 1, 2, 3, 4 and 5. Experimental results show that all four parallelizations had a tendency of showing reduced execution time as increasing the number of threads. However, it was observed that the amount of increases in speedup and the efficiency decreased as the number of threads increased. For example, if two threads are used, the time is roughly twice as fast as using one, but when using 4 or 8 threads, the time does not decrease in proportion to the number of threads.

In Fig. 1, the speedup is drastically decreased when increasing the threads from 16 to 48. The contributing factor for this result would be that the amount of work for a single thread to carry out is relatively smaller than the thread start-up overhead.

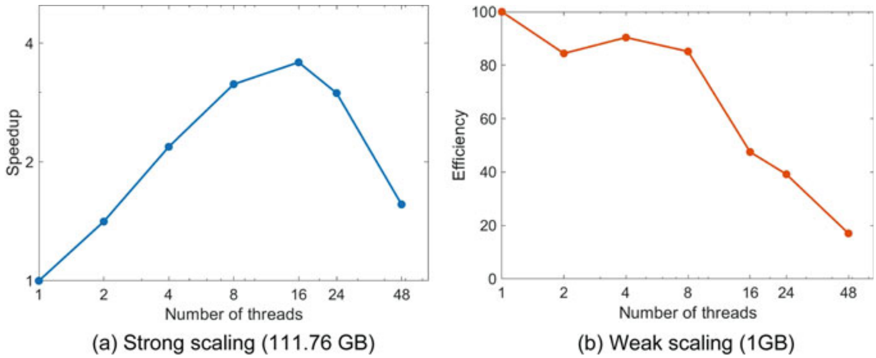

Fig. 1 Normalization results

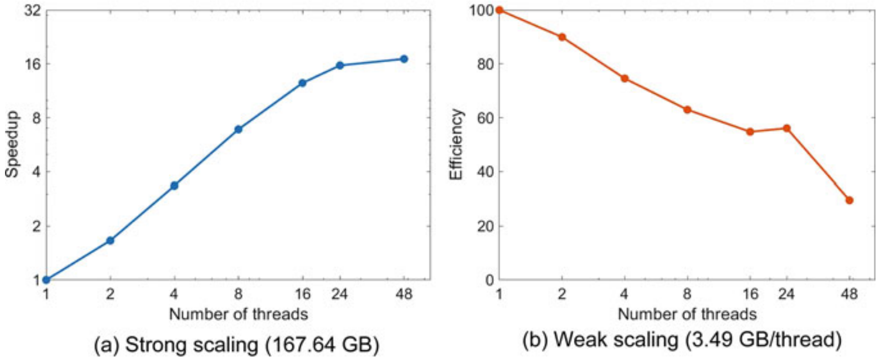

Fig. 2 Distance matrix calculation results

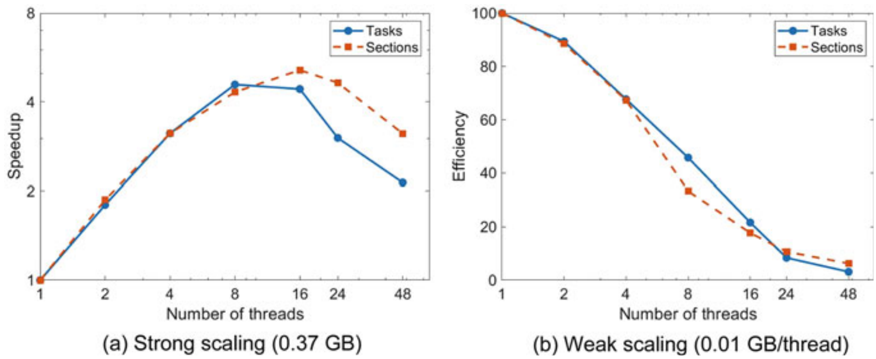

Fig. 3 Parallel merge sort results

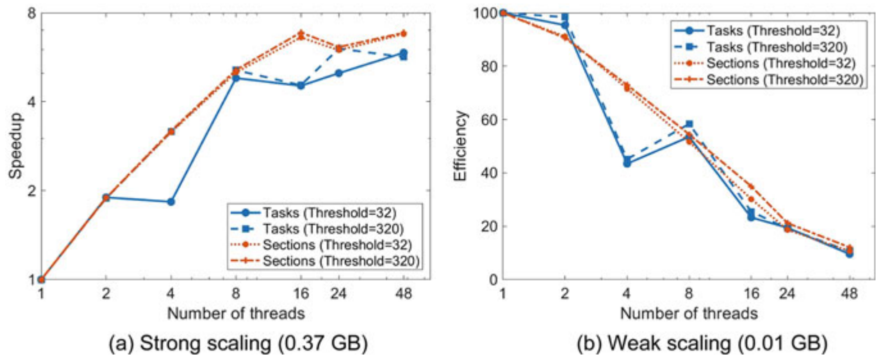

Fig. 4 Revised parallel merge sort results

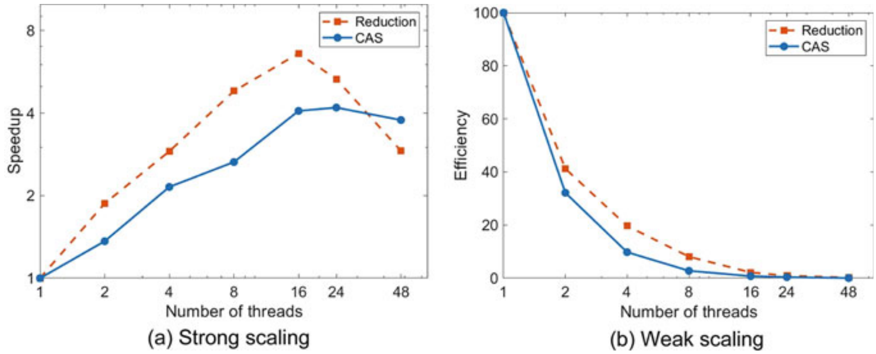

Fig. 5 Prim results

In other words, executing more than 16 threads for parallelization is more time-consuming than calculating the minimum and maximum values and replacing the normalized value for each element. Calculating a distance matrix showed the highest parallel efficiency among the experiments as can be seen in Fig. 2. Linear increases were shown for the speedup and the highest speedup of 17.05 was observed when using 48 threads.

A serial merge sort algorithm was parallelized by using OpenMP 'sections' and 'task' constructs. Figure 3 depicts the results from executing Table 5. In both cases, there were decreases in speedup when increasing the number of threads from 16 to higher number. Through a careful inspection of the codes, three major contributing factors could be revealed. When using 'sections', calling the parallel directive (i.e., #pragma omp parallel sections) instructs the computer to spawn a group of threads and the recursive calls would generate unnecessary threads which yield oversubscription. For example, setting 16 threads in the initial phase of the program would create a team of 16 threads in each recursive call. To mitigate this problem, one strategy is to set the number of threads equal to 2 (i.e., using num_threads(2)) since we have two sections, and track the number of available threads in each level of the call tree to stop dividing the work. Similarly, having the parallel directive inside the sort function would create a thread team in each recursive case and significant overheads would be generated. Thus, declaring the parallel region outside the initial sort function call would create threads pool once and it can avoid overheads of creating threads multiple times. Also, Radenski [15] suggested to use insertion sort in the case when the number of elements in the array is smaller than the user-defined value (i.e., initially 32 in this project) since non-recursive methods outperform recursive merge sort for small arrays.

However, it is important to note that overheads of creating threads would possibly overwhelm the execution time when very small chunks of work are assigned to the thread. Thus, the array size for implementing insertion sort should also be considered as an experimental factor. Table 5 was revised considering these factors and the result is provided in Fig. 4. Compared to the results in Fig. 3, both cases using 'sections' and 'task' showed improved performance in strong scaling that the speedup tends to increase until using 48 threads. Also, setting a larger value (i.e., 320 elements) for converting to insertion sort showed significant improvement for 'task' while marginal increase was shown for 'sections'. Overall, parallelizing merge sort did not show such significant performance deviation between 'sections' and 'task'. One of the reasons would be that the merge sort algorithm is itself a well-balanced algorithm that dynamic nature of tasks could not produce such benefits over the controlled environment of 'sections'. At the same time, the overheads of task generation would be responsible for degrading the performance.

Lastly, in the case of parallelizing Prim's algorithm, both reduction and CAS results showed increases in speedup until 16 threads while reduction operation had slightly higher performance except for the case using 48 threads. One of the reasons for reduction function showing better results is that leveraging CAS requires higher frequency of logical operations when synchronizing the atomic values. Also, in general, the execution time was measured for the entire MST algorithms which consists of finding minimum value as well as updating the new key values. Thus, the parallelization was not optimally implemented for the whole parts that opportunities remain to improve the overall performance.

6 Conclusions

In this study, the main objective was to parallelize four sub-steps of HDBSCAN using OpenMP. The sub-steps are: (1) normalization, (2) calculating distance matrix, (3) merge sort, (4) Prim's algorithm. Parallelism could be observed when increasing the number of threads for executing each parallelized algorithm. However, the performance did not improve proportional to the number of threads and some cases showed decrease in performance above specific number of threads. There are several reasons that would explain the results. Firstly, in case of merge sort and Prim's algorithm, although some parts are parallelized with the multiple threads, sequential parts are still remaining that theoretically there is an upper bound for speedup according to Amdahl's law. Another common reason for all cases would be the latency to start execution of the parallel tasks. Although the work time is parallelized with multiple threads, the amount of time to initiate the team of threads and launch all the separate works would become a large portion of the processing time. In addition, there are bandwidth issues that threads updating different values could frequently hit the same cache line which would slower the total execution time. In overall, our experiments have shown how the parallelization strategies could mitigate the data size issue in our construction domain.

Acknowledgements This research was supported, in part, by the National Science Foundation (NSF) under award number 1562438. Their support is gratefully acknowledged. Any opinions, findings and conclusions, or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation. Mention of trade names in this article does not imply endorsement by the University of Texas at Austin or NSF.

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Comparative Analysis of Energy Harvesting Methods in Transportation

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1 Introduction

Within the past decade, the world has seen exponential growth in population and consequentially in energy consumption. Currently, more than 50% of the world's population lives in urban cities, and by 2050, global urbanization will continue leading to even higher populations and energy consumption rates [1]. The current energy paradigm relies on fossil fuel combustion, which has not only made us economically dependent on this form of energy but also has caused substantial environmental damage within the past decades. With the rapid depletion of natural resources and a looming energy crisis, how will the forthcoming populations go about being sustainable while also preserving the environment? Renewable energy is the answer. There are always the mainstream sustainable energy methods, primarily on the macro-scale, with technologies implementing wind, solar, thermal, and water-powered large-scale electric generation plants. However, as of recent, there has been more interest in energy harvesting on a micro-scale. This includes the use of solar radiation, thermal gradients, pressure, and vibrations [5]. All aspects which are available within one the heavily used yet least utilized commodities, paved roads. In the U.S alone there are approximately 4 million miles of roads and this number is continually growing with rapid urbanization. These roads are subjected to different types of energy primarily in the form of solar energy, thermal energy, and mechanical energy.

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S. Walbridge et al. (eds.), *Proceedings of the Canadian Society of Civil Engineering Annual Conference 2021*, Lecture Notes in Civil Engineering 247,
https://doi.org/10.1007/978-981-19-0968-9_44

Unfortunately, most of these energies are wasted due to a lack of efficient energy harvesting techniques (Duarte and Ferreira, 2016).

The aforementioned introduction poses an inevitable question, why should the transportation sector consider investing in the construction of more efficient energy harvesting devices? As we look into the future, the emergence of connected and autonomous vehicles (CAVs) will change the transportation infrastructure. CAVs have the potential to alter transportation systems by averting deadly crashes, increasing road capacity, saving fuel, and lowering emissions. However, the increased computerization that is to come with CAVs will lead to greater energy demand [3]. These improvements in the transportation sector would usually be paid by taxes obtained through the gas tax. But as CAVs become more fuel-efficient and with automakers aiming towards an all-electric near future, the funds obtained from the gas tax will be in jeopardy. This will in turn endanger the financial sustainability of the transportation infrastructure. Without financial support, the transportation sector may not be able to maintain its infrastructure (Terry and Bachman, 2019). If the transportation sector can harvest energy for itself and make this energy available to other sectors, it would tremendously help in terms of both financial and energy sustainability.

The most common energy harvesting methods in the transportation infrastructure rely upon solar energy, thermal energy, and mechanical energy. Solar energy is collected by photovoltaic cells which convert solar energy to usable electric energy. During construction, these cells can be embedded directly into the pavement or placed alongside roadways. Thermal gradients (the ratio of the temperature difference between two points and the distance between the two points) within pavements are used by thermoelectric generators and asphalt solar collectors (ASC). During roadway construction, both devices are placed directly underneath the pavement to absorb and convert thermal energy into usable energy. Lastly, mechanical energy is utilized by piezoelectric materials. These materials are placed directly underneath the roadway asphalt. Mechanical energy is then transferred from vehicles, through the asphalt, and to the piezoelectric materials which convert the mechanical energy into usable energy.

2 Literature Review

The following sections highlight the advantages and disadvantages associated with each of the three aforementioned energy harvesting methods in terms of applicability, energy source, energy production, and primary challenges. These methods are solar energy harvesting, thermal energy harvesting, and mechanical energy harvesting. An overall summary of each method will be given through literature review and case studies relating to the respective harvesting method.

2.1 Solar Radiation Harvesting in Pavement

Solar radiation harvesting relies on photovoltaic cells which convert light directly into usable energy. There have been many different methods to utilize photovoltaic cells for roadways. One method is constructing the roadway with the photovoltaic cells directly embedded into the pavement. Researchers from the Korea Institute investigated the viability of this technique and concluded that embedding the solar cells directly into the pavement was not feasible as the solar cells are unable to handle the large mechanical loads placed upon by the vehicles [10]. According to the investigation, the solar cells also experienced premature corrosion due to environmental conditions. Combined with high installation and maintenance costs, this is not a feasible solar energy harvesting method. A solution to this problem is the construction of a high-strength transparent layer photovoltaic pavement surface [20]. Underneath this transparent layer would be high-purity silicon photovoltaic cells. The top layer would serve to block out the elements while sunlight is able to pass through into the solar panel layer and convert solar energy into electric energy. The top layer would not only act as a means of energy harvesting but also act as a roadway. Unfortunately, the maintenance and construction of such an intricate structure would outweigh the cost over the benefits. Also, there is an argument that using the transparent top layer as a pavement would result in a lower grip in vehicle tires [20]. Towards the end of 2020, the city of Peachtree corners in Georgia implemented the first solar road in the United States using embedded solar planes in the road. The energy generated by this segment of road in Peachtree Corners will be deployed at electric car charging stations [21].

Transparent photovoltaics (TPV) is an efficient and practical way of producing renewable energy [14]. There are approximately nine transparent photovoltaic (TPV) technologies under development, and studies regarding these technologies aim to achieve high transparency along with electrical performance that is compatible with solar panels that are sold in the market [7]. The transparent and semi-transparent photovoltaic has been used in buildings with its multifunctional roles as electricity producers, building envelope components, and glazing components [12].

A more effective benefit–cost ratio method is to use solar panels along the sides of roadways. These panels would have a dual function as panels for collecting energy and acting as a noise wall/sound barrier. Sound barriers are typically constructed with steel, concrete, or masonry. These structural materials can easily be replaced with photovoltaic cells for solar energy. Although solar cells themselves are expensive, the construction, maintenance, and installation of these structures along the sides of the road are much easier and less expensive in comparison to the direct embedment of solar cells into roadways. This method of solar energy harvesting in transportation infrastructure has been utilized in practice to power signals and traffic lights along roadways (Sharma and Harinarayana 2012). The comparative analysis of the types of solar energy harvesting methods in roadways is presented in Table 1.

Table 1 Comparative analysis of types of solar energy harvesting methods in roadways

	Embedment of solar cells into roadways	Transparent and semi-transparent photovoltaic roadway	Solar cell panels along roadways
Roadway Influence	• Roadways act to harvest energy and serve as a mode of transportation	• Roadways act to harvest solar energy and serve as a mode of transportation	• Solar panels alongside roadway instead of on the roadway • Roadways unchanged
Energy Source	• Solar energy	• Solar energy	• Solar energy
Vehicular Load Bearing	• Solar cells unable to handle large mechanical loads of vehicles, leading to damage	• Solar cells are not affected by mechanical loads of vehicles as vehicles travel on transparent roadway	• Solar cells not affected by mechanical loads of vehicles as cells are alongside the roadway
Exposure to Natural Elements	• Constant exposure to natural elements	• Solar cells not exposed to elements • Transparent layer may become dirty and inhibit solar cell efficacy	• Constant exposure to natural elements
Cost	• Expensive to install, maintain, and repairs	• Expensive to install, maintain, and repairs	• Cheapest to install, upkeep and repair
Main Challenge	• Continual damage done to solar cells from large loads and natural exposure	• Natural exposure to elements hindering the amount of light getting through transparent layer	• Upkeep and maintenance of solar cells

2.2 *Thermal Energy Harvesting in Pavement*

Roads have a high rate of thermal energy absorption from both solar radiation as well as friction generated from vehicles. Unfortunately, the thermal energy is wasted and brings about negative side effects such as pavement rutting and the urban heat island effect. By harvesting thermal energy, the pavement temperature can be reduced which can increase the longevity of the pavement [25]. Thermoelectric generators (TEGs) are one of the technologies used to convert the thermal gradient within pavements, created from thermal energy, into usable energy. During roadway construction, thermoelectric generators can be housed directly within the pavement. These TGEs utilize the thermal gradient through the Seebeck effect where a voltage difference is created by having a temperature difference between the hot and cold sides of the TGE (Jiang et al. 2019). The hot side of the TGE absorbs the heat of the thermal gradient while the opposite side is kept cool, usually by water [25]. The temperature difference between these two sides drives a voltage difference which in turn creates usable energy. The temperature gradient is the driving force behind the efficiency of this method as a higher temperature gradient equates to more generated energy [2]. The temperature gradient is also one of the main challenges with this method as many times the heat needed may only be applicable in hot climates. The thermal gradient must also be maintained to ensure conversion efficiency. Although research has been limited, thermoelectric energy harvesting looks to be a sustainable method of energy harvesting as it is not only able to utilize thermal energy but also reduce rising temperatures within the road prolonging the service life of the road [8].

Another common technique that has been used in collecting the heat from thermal gradients is through Asphalt Solar Collectors (ASCs). ASCs are constructed by embedding pipes within the pavement with fluid circulating inside the pipes. The thermal gradient within the pavement, caused by the solar radiation and friction from tires, is transferred into the liquid/gas flowing in the tubes [11]. The resulting heated liquid/gas within the pipes is then used to produce electricity. Just as TEG, ASC mitigates high pavement temperatures and increases the longevity of the pavement. ASC needs the road surface to have high heat absorptivity as the efficiency of the system is dependent upon the thermal gradient created within the pavement. A bigger thermal gradient results in more energy generated. It has also been recommended that the pipes be made of conductive metals for best heat transfer and for the liquid within the pipes to be as turbulent as possible [17]. These methodologies of thermal energy harvesting also has its drawbacks. Pipes are embedded directly into the top layer of the pavement and are prone to become damaged from large mechanical loads. Cracking within the road itself may expose these pipes more to increased loads and outside elements that may degrade the pipes. The fluid and gas pressure must always be kept full as even a small leak within the pipe would render inefficiency within the piping system (Zhao and Sharma, 2018). Table 2 compares the types of thermal energy harvesting methods.

2.3 Mechanical Energy Harvesting in Pavement

Approximately 20% of the energy released by vehicles is transferred onto the road in the form of pressure and vibrations. Pressure and vibrations induced on roads can be harvested with piezoelectric devices which convert the mechanical energy into electrical energy [6]. The piezoelectric effect refers to a process of using piezoelectric materials to generate electrical energy in response to applied mechanical stress, which in this case is pressure and vibration from vehicles [20]. Piezoelectric materials are classified as inorganic, organic, or composite. Inorganic piezoelectric materials consist of crystalline and ceramics. Piezoelectric ceramic materials are more efficient at converting energy but are less resistant to vibration at high frequency. While piezoelectric crystalline structures are physically stronger but less efficient at converting energy [20]. Organic piezoelectric materials have high elasticity and are capable of being made in different shapes and sizes. Combining both organic and inorganic

Table 2 Comparative analysis of types of thermal energy harvesting methods

	Thermoelectric method	Asphalt solar collectors
Roadway Influence	• Reduces pavement heat thus increasing longevity of pavement, hinder pavement rutting and urban heat island effect	• Reduces pavement heat thus increasing longevity of pavement, hinder pavement rutting and urban heat island effect
Energy Source	• Relies upon temperature gradient and Seebeck effect for energy creation	• Relies only upon temperature gradient
Vehicular Load Bearing	• Capable to withstand large loads granted pavement structure has not been compromised	• Capable to withstand large loads granted pavement structure has not been compromised
Exposure to Natural Elements	• Only exposed to natural elements if pavement structure has been compromised	• Only exposed to natural elements if pavement structure has been compromised
Cost	• More expensive to install and maintain	• Less expensive to install and maintain but relatively still expensive
Main Challenge	• Continual maintenance of thermoelectric materials to ensure efficient energy production • Mainly applicable in hot climates	• Rupture in pipes may cause fluid leaks within pavement reducing pavement structure integrity • Mainly applicable in hot climates

piezoelectric materials result in composite piezoelectric materials. Composite piezoelectric materials can have high flexibility while also overcoming the limitation of low energy harvesting and are usually the materials used in most devices (Schoneker, 2008).

Piezoelectric materials are housed in transducers that detect different forms of mechanical loads according to the vibration of the respective motions. This includes picking up the pressure a vehicle induces when it comes to a complete stop, picking up the pressure vehicles induced from the frequency of times vehicles pass a certain spot, or the bending of the pavement due to the vehicle load. Therefore, the placement of these transducers is critical during roadway construction as the placement determines the efficiency of what sort of vibration the transducer will react to. There are two primary forms of transducers, namely, cymbal transducers and cantilever transducers.

Cymbal transducers are constructed with a steel plate on top of a stretched film consisting of piezoelectric materials [20]. These transducers are ideal in instances of direct loading such as underneath sidewalks or at stop signs where vehicles come to a complete stop. Lv et al. (2015) designed a cymbal transducer of different thickness and diameters to collect energy generated on the pavement. During roadway construction, this model was placed underneath the pavement where vehicles come

Table 3 Comparative of the different piezoelectric transducers

	Cymbal transducers	Cantilever transducers
Roadway Influence	• No influence on roadway	• No influence on roadway
Energy Source	• Mechanical energy transferred. Activated during direct loading onto piezoelectric materials	• Mechanical energy transferred. Activated during bending of piezoelectric film
Load Bearing	• Capable of taking large loads. Dependent upon placement depth of transducer	• Capable of taking large loads. Dependent upon placement depth of transducer
Placement Locations	• Located in areas such as stoplights and stop signs	• Located in areas such as speed bumps, stop signs and stop lights
Cost	• Less costly than cantilever transducers. Cost depends on type of piezoelectric materials used	• More costly than cymbal transducers. Cost depends upon length of transducer
Main Challenge	• Maintenance of transducer due to depth of transducer placement	• Maintenance of transducer due to depth of transducer placement

to a complete stop. The deformation of the road caused by the vehicle load size was proportional to the energy generated (Lv et al. 2015). Cantilever transducers have a thin piezoelectric film attached at a free end of a cantilever beam. Energy is created by the increase in deformation of the piezoelectric plate [20]. Chen et al. (year) presented a cantilever transducer for road speed bumps. As a vehicle began to slow towards the speed bump the mechanical force at the free end of the cantilever begins to increase from the vehicle load, which bends the piezoelectric film and generating electricity. Table 3 summarizes the distinctions between the cymbal and cantilever transducers.

3 Comparative Analysis of Energy Harvesting Methods

Each method of energy harvesting has its strengths and weaknesses. Some generate large amounts of power but are susceptible to degradation while others require less maintenance but generate low amounts of power. The following section will look at each of the three energy harvesting methods in terms of energy production, drawbacks, and future technology development. Lastly, the section will close with an introduction to e-Roads which are energy roads that can consider all three methods of energy harvesting methods.

Out of the three-energy harvesting methods, solar energy harvesting provides the greatest power density at approximately 10^4 (μW/cm^3). However, this level of energy conversion only occurs during bright and sunny days. During cloudy days the power density of solar energy harvesting is significantly hindered and is almost halved at 10^2 (μW/cm^3) [20]. This is one of the bigger setbacks for solar energy as it is weather-limited. The potential energy generated is also dependent on the solar irradiance of the location which in the United State varies from over 5.75 kW/m^2/Day to under 4.00 kWh/m^2/Day. Although it can be harvested in more southern and temperate regions, more northern regions that do not have as much access to the sun will not be able to efficiently harvest solar energy. Thankfully, solar energy harvesting is one of the most researched topics. Solar energy is one of the leaders of renewable energy and has gained continual interest over the past few years. With more advancements in solar energy harvesting, these methods will become much more efficient in the future.

Thermal energy harvesting has the lowest energy turnover out of the three energy harvesting methods. This is predominately due to the requirement for a large temperature gradient in the roadway. Although this may be applicable in large cities located in temperate climates, this is not an ideal energy harvesting technique in most regions. Thermal energy harvesting also requires significant upkeep and the methodologies used for harvesting are difficult to repair. Both thermoelectric energy harvesting, and asphalt solar collectors have equipment housed directly underneath the roadway. Repairing these structures would cause an entire roadway to become closed and create delays. If this were to occur on a large scale across an entire city this would cause significant traffic problems.

Mechanical energy harvesting through piezoelectric materials provides the second greatest power density at approximately 10^2 ($\mu W/cm^3$) [20]. Although the energy conversion rate is lower than that of solar energy, mechanical energy harvesting is not limited to weather. This is because no matter the weather mechanical energy will always be transferred into the road from vehicles. Mechanical energy harvesting can also be implemented in many different designs. This phenomenon relies upon piezoelectric materials. Research within mechanical energy harvesting is ongoing and still very much in its infancy. However, the potential with mechanical energy harvesting far outweighs that of solar energy harvesting and thermal energy harvesting. This is because of the continual mechanical forces that are put upon roads due to vehicles. Unlike thermal and solar energy harvesting which rely upon weather, mechanical energy harvesting does not. Table 4 gives an overall outlook on the three different energy sources in terms of their harvesting methods with 3 representing the highest rank and 1 the lowest rank.

Current energy harvesting methods only focus on one or two ways to achieve energy conversion [5]. However, the most sustainable method towards using urban transportation infrastructure for sustainable energy harvesting is by using a combination of all methods mentioned and forming energy roads (e-Roads). Establishing e-Roads would require a holistic approach that considers construction and reconstruction of roads and look at energy modes available at certain sections of roads to ensure the e-Roads work together as an efficient system [15].

Table 4 Overall outlook on the three different energy harvesting methods

Criterion	Solar energy	Mechanical energy	Thermal energy
Energy production	3	2	1
Maintenance	3	2	1
Cost	3	2	1
Longevity	2	3	1
Load bearing	1	3	2
Current applicability	3	2	1
Future applicability	2	3	1
Average	*2.4*	*2.4*	*1.1*

4 Conclusion

Harvesting energy through piezoelectric, thermal, and solar energy in our transportation system can supply additional energy in the future. Urban planners, engineers, and construction workers must diligently work together to make sure the integration of these different energy harvesting methods in the transportation infrastructure can be implemented in a holistic approach. Effectively harvesting the energy from the urban transportation grid supports not only the needs of the transportation sector but also the needs of the national grid and acts as a path to our sustainability. Solar radiation can be harvested through photovoltaic cells in regions where there is sufficient sunlight. These cells can be embedded directly into the road or can be lined alongside the roadway. Thermal energy harvesting methods look to take advantage of the thermal gradients that are created in the pavement. Thermal gradients can be harvested by using asphalt solar collectors which use pipes filled with fluid underneath the asphalt to collect the thermal gradient temperature or thermoelectric materials which use voltage differences from the thermal gradients to create usable energy. Mechanical energy harvesting takes advantage of the mechanical energy that is transferred from vehicular loads directly into the pavement. Transducers comprised of piezoelectric materials are housed within the pavement and cover the mechanical energy into usable energy. Overall all three of these energy harvesting methods can be used to generate renewable energy within the transportation sector, but research within solar energy harvesting and mechanical energy harvesting looks to be the most promising. Future studies will look to plot more information regarding energy output and a more thorough look into the costs of making and maintaining the respective energy harvesting materials.

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Lessons Learned from UNLV's Solar Decathlon 2017 Competition Experience—Design and Construction of a Modular House

Julian Prestia, Jin Ouk Choi, Seungtaek Lee, and David James

1 Introduction

Since 2002, the United States Department of Energy (DOE) has hosted the Solar Decathlon competition, in which college and university students are required to design and build their own fully-functional solar house, competing against other universities across the globe in ten-events that gauge the home's performance, usability, and market potential as a solar house. The Solar Decathlon's main objectives are to (1) prepare and train students for the clean energy workforce; (2) educate students on the latest technologies for energy efficiency, clean energy, and green buildings; and (3) demonstrate the high-performance houses to the public [22]. Experts judge six juried events, and there are four contests where measured data are obtained and evaluated.

The UNLV team participated in the 2017 Solar Decathlon competition with a trailer-mounted modular house design. The team designed, fabricated, and constructed a sustainable modular house built in two sections to be joined at the competition site. The project team consisted of multidisciplinary groups that included students, faculty, and experts from various fields, such as architecture, engineering, construction management, health sciences, and marketing.

As mentioned above, the UNLV team chose a modular construction method because it proved to be beneficial for sustainable performance [4, 6, 14–15, 20, 21, 25], as well as to achieve the Solar Decathlon competition's objective. Modular construction can reduce construction waste, as well as the amount of used material compared to conventional methods [13]. As most modular construction work is

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S. Walbridge et al. (eds.), *Proceedings of the Canadian Society of Civil Engineering Annual Conference 2021*, Lecture Notes in Civil Engineering 247,
https://doi.org/10.1007/978-981-19-0968-9_45

carried out in a specialized factory, materials are used only as needed. Additionally, the remaining materials can be stored and reused in the next project.

Modular construction also mitigates construction-related site-disruption, along with dust and noise creation on site. For instance, construction dust emission can be reduced by 30% because the factory-made modules are transported and assembled like building blocks at the construction site [17, 18]. Modular construction almost eliminates building demolition waste and contamination because the modules can be dismantled, relocated, and reused.

Modularization also has cost-saving advantages [5, 24]. According to a recent report, modular projects can reduce costs by up to 20% [2]. Modular construction can also shorten project schedules [5, 23, 24] as up to 50% of the project duration can be cut [2] because modular construction increases the overall productivity due to increased labor productivity, parallel construction, and minimal weather impacts. Moreover, it shows better performances with respect to labor productivity (McGraw-[2, 19], quality [2, 5, 24], and safety [5, 7, 24]. Compared to the conventional stick-built that embeds enormous non-value adding activities (wastes) in their construction process [3], modular construction can reduce non-value adding activities significantly by implementing a lean principle together. Furthermore, modular construction technique can facilitate the post-disaster reconstruction [10].

Despite these benefits, modular construction has several difficulties and challenges in practice. The first difficulty is a high initial project cost [11, 16] because additional project costs exist for planning, design, and procurement [24]. Second, modularization requires more extensive coordination, as well as earlier and more frequent communication [9, 11, 12]. Third, the logistics are challenging. Modules are usually larger and heavier than conventional construction materials and parts, so heavy and mega-lift cranes are necessary. Sometimes, an extra construction space is required for the modules' assembly [1]. The logistical barrier can be even worse if the site is located in a high-density urban area [5]. Transportation restrictions can constrain and limit the modules' size [8]. Several studies have been conducted on the difficulties and barriers of modularization, but few studies have been conducted about failures of or lessons learned from modular projects in practice.

This research aims to provide information from the UNLV Solar Decathlon project experience to help future projects make better decisions in future modular projects. The objective is to identify the main issues experienced by the 2017 UNLV team using a qualitative case study and then explore how those problems were either alleviated or could have been avoided. The final goal of this paper is to provide a comprehensive summary of the issues faced and overcome by the 2017 UNLV team. The remainder of this paper is organized as follows. Section 2 introduces the 2017 UNLV Sinatra Living House (note: UNLV obtained permission from the Frank Sinatra Foundation to use "Sinatra Living" for the non-commercial purposes of the competition). Section 3 explains research and data collection methods. Section 4 provides the interview results and the discussions based on the interview.

2 2017 UNLV Sinatra Living House

For the 2017 competition, the UNLV team proposed a housing prototype that met rising regional and national demands for sustainable homes that offer safety, independence, diagnostic capability, and comfort to elderly and disabled populations. The primary goals of this project were to meet the physical and psychological needs of an "aging in place" market while simultaneously creating a sustainable design for living in the Mojave Desert and its harsh climate. It should be stated that the provided solution does not currently exist at the community level in Las Vegas. Statistics drove Team Vegas' design strategies. Life expectancy is steadily rising due to health-care and technological improvements in the United States, and the 50 and older population will increase approximately 20% by 2030. Also, more than 20% of the population will be older than 65 by 2050. Though older adults live longer and stay healthier, many eventually face the practical challenges of aging and disability. This project was expected to contribute to improving older individual's environmental quality of living.

Figure 1 shows the exterior of the house. The solar home built by Team Vegas had a total floor area of 970 square feet and was assembled on two chassis modules (in essence, a double-wide trailer home). Figure 2 shows the house chassis system. The approximate combined weight of the modules for the project was 29 metric tons. The larger one weighed 14.4 metric tons. The larger module is approximately 16 ft (4.9 m) tall (with a sloping roof at a six-degree angle), 40 ft (12.2 m) long, and 13 ft (4.0 m) wide. The modules were transported and installed at the Denver, CO,

Fig. 1 2017 UNLV Sinatra Living House

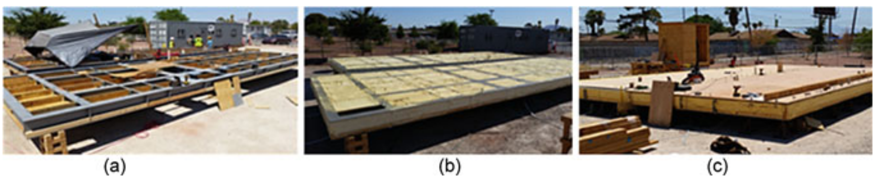

Fig. 2 House chassis system; **a** painted chassis with bottom boards; **b** insulated; **c** subfloor installed

USA, 2017 Solar Decathlon competition site with student laborers and professional assistance.

Some of the project's interior highlights are:

- The adaptability of the house allows for customizable spaces or additions to the structure. As the residents' housing requirements change with age, additional modules could be added to accommodate them.
- Optimum orientation is an east-west direction for best solar energy collection and a single rectangular loop floor plan to maximize the interior living space and permit room for persons with walkers and wheelchairs to circulate through the house.

The energy was generated using a 6 kW solar photovoltaic array and a solar thermal system for hot water and floor heating, as shown in Fig. 3. The photovoltaic array was supplemented with a Tesla storage battery and inverter that could be used when the area lacks sunlight. A mechanical pod on the south deck housed the home's solar thermal collector, controls and two-loop storage tank, and A/C condensers connected to the home's three mini-split air conditioner/heat pumps. All HVAC, energy, water, and lighting systems were integrated into the home's automation system for control and monitoring. All systems were tied through the Amazon Echo device and could be controlled or adjusted by giving voice commands to Alexa.

The home utilized a radiant floor heating system as the primary source of heating. Figure 4 shows the radiant floor heating system. The home used another isolated loop located at the top of the storage tank to heat water returning from the floor system to 90° by using a mixing valve for circulation through the home.

For ventilation and air conditioning, the house used mini-split heat pumps for cooling, and redundant heating and, to maintain indoor air quality included an air exchange system that utilized phase-change materials for temperature adjustment. The home could also remove humidity using a dehumidification mode on the heat pumps.

Fig. 3 Solar thermal units; Tesla storage battery; mechanical pod interior with storage tank and controls

Fig. 4 Radiant flooring system (PEX Tubing)

Fig. 5 Gravity-fed grey water planter

For water conservation, the house was equipped with water-efficient fixtures and appliances. The home automation system monitored and recorded the home's water usage to allow occupants to see changes. This system would enable the homeowner to resolve leakage issues promptly. Black and grey water were separated in the waste vent plumbing; the greywater could be reused for irrigation, as shown in Fig. 5.

During the 2017 competition's ten contests, the UNLV entry won first place for innovation, tied for second place for architecture and engineering, and placed eighth overall out of eleven entrants.

3 Research Methodology

3.1 Data Collection

This research adopted a qualitative-based case study to obtain information about the Solar Decathlon 2017 competition team's design and construction experience. The student project manager, student project engineer, and student construction manager were all contacted to provide information, solutions, and personal experiences from the event. The project manager and construction manager responded with their personal opinions based on their experiences during the 2017 competition and the previous 2013 competition. Survey data were collected through questionnaires comprised of specific questions regarding best practices and the lessons learned during the design, construction, and competition phases from the project manager and construction manager. The information provided illustrates a comprehensive understanding of what problems were experienced during the design, construction, and competition phases and how they were overcome.

3.2 Interview Questionnaire

The questionnaire was comprised of five specific questions (and a section for additional information) regarding matters related to the best practices and lessons learned from any issues experienced during the construction and competition phases of the 2017 competition. All the five questions can be found in Appendix. Their responses, as well as personal experiences are used to determine the best practices and lessons learned. In this way, future teams conducting modular projects can learn from this experience and make improvements.

4 Results and Discussions

4.1 Interview Results

In-depth interviews were conducted with the project manager and construction manager. They participated in the project from beginning to end, so they understood the tasks and circumstances well. Table 1 summarizes the interview results.

The first question was about the significant problems experienced during construction. Both respondents indicated the same problem: the incomplete chassis design. The student project manager mentioned that the student structural design team operated separately from the rest of the design teams, with few interactions or updates throughout the design process. Eventually, the design team graduated, and the responsibility passed to a professional firm that was unclear about the full scope of work. Due to the lack of communication between the student team and the structural firm, chassis fabrication was postponed for approximately five months, which crunched the construction window by a significant margin.

The student construction manager also criticized the incomplete chassis design as the main issue. Due to the design problems, the project lost time for testing and adjustments. The student project manager also indicated that there was not enough time to reconstruct the modular house at the competition site because of delays. The construction manager also mentioned that there was an insufficient student workforce at the site, and there was too much work to be done by the student workforce.

Table 1 Interview summary

	Student project manager	Student construction manager
Major problems	• Incomplete chassis design • Not enough time to reconstruct the modular house at the competition site	• Incomplete chassis design • Lack of workforce
Problem solutions	• Permanently welding the hitch to the chassis	• Constant communication • Increase the number of paid positions and support expenses
Suggestions for future	• Find a structural engineer with experience in modular transportation • Hire a general contractor	• Acquire multiple estimates before choosing a firm • Increase labor incentives to increase involvement • Have a dedicated student budget analyst • Increase communication and efficiency

To address the incomplete chassis design problem, the student project manager found a vendor to weld hitch reinforcements onto the chassis. The student construction manager constantly communicated through calls, emails, and structural engineer visits. Moreover, a good fabrication company was chosen to complete the chassis package within a month. Also, to increase the workforce, the construction manager increased the paid student positions, as well as support expenses for lunch, drinks, and snacks in order to form a sense of companionship.

The questionnaire also requested information about how to avoid these problems in the future. The student project manager suggested that the best route with the structural issue would be to find a structural engineer comfortable with the team and the scope of work required for modular transportation, and also indicated early meetings and defined work would be helpful. Moreover, hiring a general contractor to organize the construction effort would be beneficial because the team was already stretched thin between the project, school, and other jobs. A general contractor would be able to handle schedules, order materials, and keep the team on task to meet deadlines.

With respect to organizing the work, the general contractor could have the students do most of the work or hire competent subcontractors for specialized work (both options are allowed for the competition). The student construction manager made four recommendations for future student projects.

(1) Acquire multiple estimates before choosing firms and generate a contract with that firm as quickly as possible.
(2) Provide incentives, such as paid hours or additional credit hours to boost student involvement, and reduce material costs to increase the available labor budget, which would provide an opportunity to create more student involvement.
(3) Designate a dedicated student budget analyst to track purchases and oversee the construction budget.

(4) Increase communication and efficiency while freeing up the primary advisor for more demanding concerns, such as permits, contracts, construction, and travel schedules.

4.2 Best Practices and Lessons Learned

Based on insights from key student personnel, the main problems faced during the construction phase were mechanical issues about the chassis hitch, structure, and engagement with the structural engineer, as well as the lack of communication and organization throughout the project that created additional unnecessary stress between team members and key personnel.

Problems faced during the competition phase were primarily the time crunch due to late arrival associated with completing the modules before transportation. Arriving at the competition five days late hindered the team's ability to present the best house they could build. Although the house was completed to a level that allowed competition participation, a few components, such as powered deck and window shades, were not installed due to lack of time. Having more time to complete the house in Las Vegas would have alleviated some of the stress experienced by the engineering students who had to run all the system tests in Denver rather than in Las Vegas. The chassis fabrication delay reduced the time window available for assembling the modules at the competition site in Denver. Had the design been finalized earlier, the house could have probably been thoroughly tested prior to leaving for Denver.

The solution for the chassis hitch issue was to weld reinforcements at the point of the bolted chassis attachments to provide additional structural support. An improved approach in the future would be to engage the structural engineering team earlier and interact with them more often during the project.

A dedicated larger enclosed work area, near the project site in which all disciplines and team members could work together and exchange information freely, would provide quicker and additional communication, along with a better understanding of the project from all team members, as they would be exposed to all aspects of the project and not just the specific portions they are helping to design.

For the lack of organization, a professional general contractor's introduction to organizing the students' efforts would be the best solution. A professional would help determine real-world solutions to potential problems, and they would be much better equipped to handle the stresses of running a project. Some key personnel did an excellent job at their roles; however, some students lacked the ability to take on the amount of responsibility they had signed up for on top of their coursework. A skilled general contractor would help organize all aspects of the project and create a much more comprehensive and legitimate schedule for all students and subcontractors to work more efficiently and effectively while on site. Additionally, the schedule and all information related to the project should be provided and readily available for all team members to view, so they could better understand the process.

There was some information about the previous UNLV team's experiences in 2013, but there was no comprehensive guide or booklet about how the previous team was able to accomplish what they did. To preserve and transmit lessons learned from the 2017 competition, it is recommended that the university communicates with each student, faculty member, and professional involved in the project to create a much more complete version of a 'lessons learned' document. Collecting and organizing information about all of the issues, big and small, experienced throughout the 2017 competition would provide insights into addressing issues associated with design, construction, and competition. Furthermore, additional communication between teams and skilled trades helps all participants understand what the team is trying to accomplish for each part of the house.

The suggested best practices for future UNLV Solar Decathlon would include.

- Hire a general contractor for project organization and managing major project phases, to keep everything running smoothly.
- Maintain consistent and frequent communication throughout the design phase among all design teams to keep everyone informed about all aspects of the house and create a stronger bond among team members, leading to quicker solutions.
- Catalog events as they are experienced and assemble into an accessible document at the end of the that would be useful for subsequent teams competing in future projects. This would provide a comprehensive and detailed experience to help future teams avoid the same mistakes and build on the discovered solutions.

5 Conclusions

This paper describes the UNLV Solar Decathlon team's experiences in preparing an entry for the 2017 competition. The main issues and solutions to those issues were discussed using in-depth interviews completed by key student project personnel. The survey responses provided by the student project manager and student construction manager offered insights into the technical and construction issues encountered during the project and describes how one major technical problem was addressed. Also, best practices for future modular house construction were suggested.

6 Recommendations

With regard to follow-up steps, additional research and data compilation regarding the 2017 house's strength would help improve future modular construction projects. Improved curricular integration by the university could help students prepare for the Solar Decathlon and expand their understanding of how they can use what they are learning in school to solve real-world problems.

Acknowledgements The authors express their gratitude to the interviewees who donated their time to this study. The authors also thank UNLV's Solar Decathlon 2017 team members for their excellent work and success in their competition.

Appendix

Solar Decathlon Survey

Please answer the following questions to the best of your ability, the information provided from these surveys will be compiled for a paper regarding best practices and lessons learned from the 2017 Solar Decathlon competition.

Name:

Project Role:

1. What were some of the major problems experienced during the construction phase through the competition phase? Please explain in some detail.

2. What solutions were used for the problems mentioned above? Please explain in some detail.

3. In hindsight, could any of the solutions be improved for the future, if so, how? Also, on that note, which problems could have been avoided and how? Please explain in some detail.

4. With the knowledge and experience you have now, would you be willing to participate in the next Solar Decathlon or comparable international events? Why or why not? Please explain in some detail.

5. Should UNLV compete, what advice would you give to the students participating in the 2020 Solar Decathlon competition?

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Investigating the Impact of Trombe Wall on Building Energy Saving and Thermal Comfort—A Case Study

M. Jalalpour and C. Nnaji

1 Introduction

According to the world energy outlook, buildings and building construction sectors account for 36% of world final energy consumption and approximately 39% of total CO_2 emissions [2]. This high amount of energy consumption and greenhouse gas (GHG) emissions are fundamental reasons to encourage and implement solutions that decrease energy usage in the built environment and negative environmental impact. In Iran, the building sector is responsible for about 36% of the total energy usage [13]. Previous studies represent that Iran is among the top ten countries in emitting GHG emissions [9, 23]. Therefore, this research tries to find techniques and designs to decrease natural gas and electricity consumption, which are two of the main types of energy usage in buildings in Iran [26].

There are various passive and active techniques and strategies that promise to resolve those issues mentioned above in building design [33]. Trombe wall (TW) system is a passive system that is posited to hold great promise in improving energy efficiency while also being less expensive and easy to construct [33]. TW is a passive system which was named after a French scholar, Professor Felix Trombe, who developed this system in 1966 [4]. There are different types of TW, and they are usually constructed with brick, concrete, and adobe [22]. In this system, a massive dark painted wall is added inside the south-facing glazing. The solar radiation will be trapped because of the greenhouse effect. The surface of this wall, which faces the sun, is painted with a dark color, and during the daytime, the temperature of this surface rises, which helps the heat flows into the wall. The Thickness of TW can be varied, but it is usually about 30 cm, and this thick wall causes a long time lag. As a

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S. Walbridge et al. (eds.), *Proceedings of the Canadian Society of Civil Engineering Annual Conference 2021*, Lecture Notes in Civil Engineering 247,
https://doi.org/10.1007/978-981-19-0968-9_46

result, heat reaches the interior surface with a long delay in the evening, and enough mass in a TW turns it into a radiant heater during night-time [20].

Multiple studies on TW performance show that TW could reduce annual heating load [7, 8, 15, 18, 30]. According to experimental and numerical studies, improving indoor thermal comfort is another positive impact of TW [1, 8, 15, 17, 18, 21, 30]. To design an energy-efficient TW, there are various variables and parameters, which are mainly effective. Type of glazing, shading, as well as wall configuration, and properties are the parameters that were worked on and discussed by researchers [8, 15, 30].

Scholars concluded that integrating TW into a building reduces annual energy consumptions and increases thermal efficiency [10, 18, 27]. However, various design configurations of TW show different results in different climates and locations [14, 28]. The basic design of TW is the classical design, and researchers are working on some design parameters on developing additional design parameters to increases the utility and effectiveness of this system in different climates [6]. For instance, Bevilacqua et al. [6] investigate the effects of adding TW in warm and cold climates, and they found a considerable energy saving in both cases. Their case study, which was in a cold climate, shows that heating and cooling loads decreased by 18.2% and 42%, respectively. In a hot climate, energy saving for the heating season was approximately 71.7%, while saving in the cooling season was about 36.1%.

Wall thickness is another parameter that directly impacts TW design. Thick walls can store solar heat in the massive wall and transfer the heat later; this method can increase thermal comfort for occupants [20]. Agrawal and Tiwari [3] worked on optimizing wall thickness, and they found the thickness between 30 and 40 cm was effective in concrete TW. In a research study by Sharma and Gupta [29], the wall thickness of 25–30 cm was proposed as an ideal width, then the massive wall absorbs extra heat during warm months and provides a stable indoor temperature.

Installing shading on the glazing of the TW could be another effective solution with the potential to increase thermal comfort and decrease the cooling energy load in summer [11, 15, 27]. Overhang shading is one of the shading types which is recommended in several studies [18, 20, 30]. Another shading solution for decreasing the cooling energy load in summer is curtain shading. Ji et al. (2007) added curtain shading in TW design for summer, and they found that indoor temperature decreased by 2 °C.

Researchers have stated the need for additional studies focused on understanding the effects of the different configurations and design on building performance in summer [5, 18, 20]. Therefore, the goal of the present study is to provide additional insight supporting the use of techniques and methods in modifications of TW that could lead to a decrease in building energy consumption. In this research, the case studies are single rooms located in Shiraz, Iran, and this city has a cold semi-arid climate [19]. This research aims to estimate both the heating and cooling loads of the rooms and calculate the indoor thermal comfort in the five cases.

2 Case Studies and Climate Conditions

The case studies in this research are located in Shiraz, Iran. Shiraz is one of the most populous cities in Iran, with a population of 1.57 million people, at the latest census in 2016 [32]. The climate of this city is classified as cold semi-arid [19] according to Köppen-Geiger's climate classification, with cool winters and hot summers.

This research aims to investigate the thermal performance of a typical residential room in Shiraz, Iran, by integrating classic Trombe wall CTW into their design. Since integrating TW had positive results in various studies [1, 7, 8, 15, 17, 18, 30], this research aims to study whether TW as a passive system is a possible solution to decrease the energy demands and improve the occupants' thermal comfort in Shiraz region. According to the literature review, TW designs perform well in cold seasons and different climatic conditions [1]. However, the performance of TW for summer overheating issues is still highly debatable [12], and it needs further investigations. Hence, in this research, both cooling and heating seasons will be studied to understand the yearly thermal behaviour of the case studies.

In the present study, annual energy consumption and thermal comfort of five cases located in Shiraz are evaluated to assess the impact of changes to the CTW design. The first case is a simple cubicle with dimensions of 10 m × 10 m × 3 m. The walls are made of brickwork and lightweight plaster. The glazing type is single clear glazing, and 30% of the facade is glazed. In the second scenario, a CTW is integrated into the first case. Here, the southern layer is covered by single clear glazing with a wooden window frame. Lechner [20] discussed the thermal mass sizing related to the TW design. In line with the information provided in Table 1, the main partition is made with black cast concrete with a thickness of 30 cm. Six rectangular vents with dimensions of 1.6 m × 0.26 m are added to the design-three at the bottom and three at the top of the design wall. This scenario is depicted in Fig. 1. In line with the suggestions made by [20] and Torcellini and Pless [31], a simple overhang shading was added to the southern glazing in the third case. This shading could be a solution to decrease the cooling load in warmer months [31]. The fixed overhang shading is made by asphalt, and this shading can decrease the direct sun energy level, which is received in the summer daytime. Regarding case 4, a shading roll, in the cooling season, covered the outside of the south glazing of the CTW of case 2. Case 5 is a CTW with both overhang shading and shading roll. A summary of the TW configuration for each configuration is provided in Table 2.

As mentioned earlier, the CTW design of our case has six vents on the main partition. In order to receive solar heat in winter and prevent overheating issues in summer, some adjustable schedules are considered. In the cooling season, vents are

Table 1 Thermal mass sizing [20]

Thermal mass	Thickness (cm)	Surface area to glazing (area ratio)
Adobe (dry earth)	15–25	1
Concrete or brick	25–40	1

Fig. 1 Wall section and front view of the TW

Table 2 Summary of the configurations of the case studies

Test room name	Design
Case 1	Single cubicle
Case 2	Single cubicle with CTW with six rectangular vents
Case 3	Single cubicle with CTW with six rectangular vents with a simple overhang shading
Case 4	Single cubicle with CTW with six rectangular vents with a shading roll, in the cooling season
Case 5	Single cubicle with CTW with six rectangular vents with a shading roll in the cooling season and a simple overhang shading

opened between 9 AM and 6 PM. In the heating season, the vents are closed between 5 AM and 8 PM. By so doing, in the cooling season, direct solar heat has less effect on indoor air temperature, and it can reduce building thermal mass at night.

3 Simulation

In this step, building thermal energy and thermal comfort calculation is conducted for an entire year for the five cases that were discussed above. The dynamic energy simulation in this research is performed using DesignBuilder 4.5, which provides results based on the EnergyPlus engine version 8.1. DesignBuilder can calculate a variety of building energy and comfort simulations. As a result, detailed thermal energy and comfort simulations for these test rooms can be conducted. In the present study, the researchers utilized the weather database of the DesignBuilder for conducting the simulation and ASHRAE climate design condition 2017 [16]. To estimate the cases' annual energy demands, for each case, heating load and cooling load are calculated. By calculating both heating and cooling loads, detailed information regarding building energy behaviour can be recognized.

The evaluation of thermal comfort in the present study is based on the ASHRAE Standard 55-2004 [24]. The goal here is to assess the changes in comfort hours made in each case. By conducting thermal comfort simulations, the design with a higher comfort level can be identified. In this paper, discomfort hours are calculated for each case to evaluate the impact of integrating the different CTW changes. Thermal discomfort includes various factors, such as when occupants cannot feel the normally expected comfort level [25]. The present study utilizes data provided by ASHRAE Standard 55-2004 [24], which determines whether the operating temperature and humidity ratio are in the standard range or not. In this standard, 0.5 and 1 are specific Clo levels used for summer and winter analysis.

4 Materials Description

This section discusses the materials and their properties used in these cases. As mentioned earlier, the external walls are made of a concrete block and brickwork. The thermal transmittance (U value) of the external wall is 1.949 W/m^2 k, and the U value of the ground floor is 0.778 W/m^2 k. The TW materials and external walls' thermal properties are reported in Tables 3 and 4, respectively.

Table 3 Thermal properties of the external walls

Material	Thickness (m)	Density (kg/m^3)	Conductivity (w/m k)	Specific heat (J/kg k)
Brickwork	0.105	1700	0.84	800
XPS extruded polystyrene	0.117	35	0.034	1400
Concrete block	0.10	1400	0.51	1000
Gypsum plastering	0.013	1000	0.4	1000

Table 4 Thermal properties of the TW materials

Material	Thickness (m)	Density (kg/m^3)	Conductivity (w/m k)	Specific heat (J/kg k)
Concrete	0.2	2100	1.4	840

5 Results and Discussions

5.1 *Building Heating and Cooling Loads*

In this section, the results of the test Cases' annual heating and cooling energy needs are presented and discussed. Various design parameters and modifications in the models give us more detail about the thermal performance of each case.

At first, building energy simulations showed that in Cases 2, 3, 4, and 5, the annual heating loads saved by 99.94%, 85.56%, 99.94%, and 85.56%, respectively. The results clearly demonstrate the effect of TW in decreasing the heating load of buildings. Also, when comparing Case 3 to Case 2, the heating load increased by 25.6%. This indicates that by installing a fixed overhang shading, which is a solution for overheating issues [20], the shading can block part of solar arrays in heating seasons. There was no observable difference between Case 4 and Case 2, in heating load demands, due to the shading roll in the cooling season. In Case 5, the added overhang and the shading roll perform similar to case 3 in heating demands. Figure 2 presents the results of the annual heating consumption of the cases.

Next, the cooling demands of the cases are calculated. As discussed earlier, CTW could have a negative effect on building cooling energy demands. The changes which were made in the design in these cases are relevant to the negative effect on building cooling energy demands. The outputs of the thermal simulation indicate that cooling loads in Cases 2, 3, 4, and 5 changed by +50.92%, +20.26%, +14.94%, −3.85%, respectively. When comparing Cases 3 and 4 to Case 2 (basic CTW), the cooling demands decreased by 20.31% and 23.83%, respectively. Therefore, we posit that the shading roll is more efficient in decreasing the cooling load, based on the examples presented in the study. Finally, the effect of combining both overhang shading and shading roll is evaluated by comparing Case 5 to Case 2, and the results present a 36.29% reduction in cooling energy consumption. The results of the annual heating consumption of the cases are presented in Fig. 3.

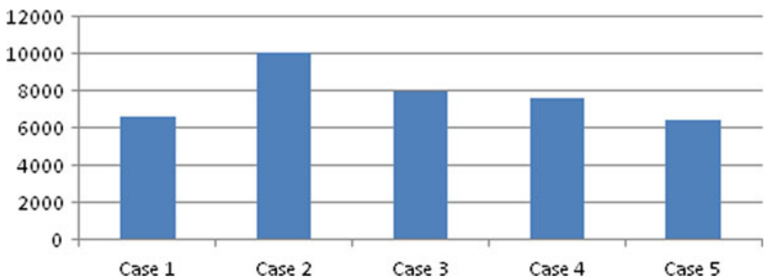

Fig. 2 Annual heating loads

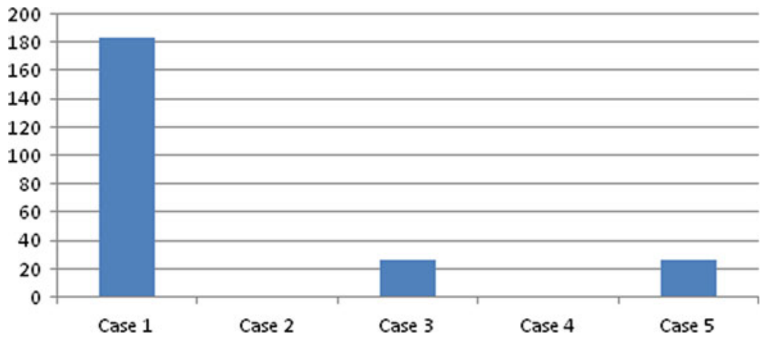

Fig. 3 Annual cooling loads

5.2 *Thermal Comfort Results*

The thermal comfort of the cases in this research was studied based on the ASHRAE standard 55-2004. Insights from calculating the discomfort hours of each case indicate that discomfort hours decreased by about 0.02% when comparing Case 1 and Case 2. This reduction is due to integrating CTW into Case 1. This implies that there is a slight improvement in comfort level when a CTW is added to the design. Cases 3, 4, and 5 also witnessed a reduction when compared to the base case (Case 1). This reduction values are approximately 0.15%, 0.25%, and 0.32%, respectively. Assessing the values of Cases 3 and 4 suggests that shading roll provides more comfort hours for occupants. In case 5, as is expected, it shows a higher comfort level compared to other cases. Hence, the results convey that all the modifications of CTW cases in this research provide a higher thermal comfort level than the base case (Case 1), which is a simple room with medium insulation. A summary of the thermal comfort results is provided in Table 5.

As described above, the heating and cooling loads, as well as the thermal comfort, could be improved using the combination of overhang shading and shading roll, which is installed in the cooling season. These results proved additional evidence of the potential utility of CTW in environments with climates similar to Shiraz, Iran. Therefore, this configuration could help resolve the overheating issue in the summertime besides operating properly in the wintertime.

Table 5 Summary of the thermal comfort results

Test room name	Percentage of discomfort hours (compared to Case 1) (%)
Case 2	0.02
Case 3	0.15
Case 4	0.25
Case 5	0.32

6 Conclusion

This research investigates the effectiveness of the CTW in Shiraz, Iran, by using DesignBuilder software to simulate building thermal performance. The simulations are conducted to understand the changes in building energy demands and thermal comfort of five proposed designs. Five cases are studied in this paper: (1) a simple cubicle, (2) a cubicle with a CTW, (3) a cubicle with an overhang shading installed on the CTW, (4) a cubicle with a shading roll that covers the CTW in summer, (5) a cubicle that both overhang shading and shading roll (in the cooling season) are integrated into CTW design.

The results show that, in this study, CTW has a profound impact on the heating season, given that it decreases building heating load significantly. For instance, it decreased the building heating loads of cases 2 through 5 by 99.94%, 85.56%, 99.94%, 85.56%, respectively. Also, the changes in the cooling season for Cases 2 to 5 are +50.92%, +20.26%, +14.94%, −3.85%. These results can highlight the negative influence of CTW in increasing building cooling load, and even with integrating TW and shading, the cooling loads increased in three cases. However, this load decreased in later design (Case 5). Another highlight from the present study is that the shading roll shows higher performance than the overhang design. The final consideration regarding heating and cooling loads is the issue related to the fixed overhang shading. This issue can be solved by installing a removable overhang shading. Therefore, the removable overhang shading cannot negatively change the building heating load in winter.

The simulations related to the building's thermal comfort show that CTW can provide higher comfort hours. In the Cases assessed in this study, discomfort hours decreased 0.02%, 0.15%, 0.25%, 0.32% when comparing Cases 2–5 to Case 1. Also, the study concludes that by modifying CTW design and focusing on the climate of building sites, discomfort hours can be decreased considerably.

Future studies should consider performing additional simulations using a complete residential or commercial building. Also, the combinations described in this study could be assessed in other climatic conditions.

Acknowledgements This research did not receive any financial support for the research, neither grant from funding agencies in the public, commercial, or not-for-profit sectors.

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Using Wearables to Monitor and Mitigate Workers' Fatigue

Zinab Abuwarda, Tarek Hegazy, Arlene Oetomo, and Plinio P. Morita

1 Introduction

Construction is a labor-intensive industry, thus, improving labor time utilization and making informed planning and scheduling decisions were recognized as effective approaches to enhance construction labor productivity [41]. Moreover, construction is the highest industry in terms of fatalities, occupational injuries, and illnesses that cost the industry $billions every year. According to the International Labour Organization, at least 60,000 fatalities occur each year on construction sites around the world. Construction workers often perform tasks that involve awkward postures in restricted spaces, high muscular loads, repetitive movements, and working with elevated arms. The resulting overexertion can lead to musculoskeletal pain in the low back, shoulder, and neck [43]. It was reported that as many as 30% of construction workers suffer from back pain and/or other musculoskeletal disorders [37]. Their work, as a result, is physically very demanding, which may not only lead to physical fatigue but also to other problems such as the loss of productivity, poor quality work, and reduced motivation and increased rework. Possible preventive measures such as proper organization of work can be used to avoid physical fatigue of workers.

In the literature, laboratory models were performed to predict workers fatigue and suggest early safety interventions, particularly in the manufacturing industry [8]. Such models, however, are demonstrating that they do not completely represent field conditions, thus indicating the importance of real-time field measurements [34]. Recently, therefore, increased research efforts have focused on non-invasive monitoring of human health as well as activity tracking using wearable devices.

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S. Walbridge et al. (eds.), *Proceedings of the Canadian Society of Civil Engineering Annual Conference 2021*, Lecture Notes in Civil Engineering 247,
https://doi.org/10.1007/978-981-19-0968-9_47

Smart watches have recently been implemented in sports, healthcare, office environment, and risky professions (e.g., firefighting, aviation, and military) to monitor a person's vital health functions [16]. In construction also, several systems exist to monitor site safety and productivity, with sensors and wearable devices used for location tracking of workers, material, and equipment. Such systems focus mainly on generating smart alerts to avoid safety and health issues, particularly under the social distancing requirements during the COVID-19 pandemic. To the authors' knowledge, little effort has been done to recognize and mitigate worker fatigue and accordingly design effective work-rests.

To monitor workers' psychological status indirectly, several indicators of physical activity exist [9]: (1) Cardiovascular indicators including heart rate and heart rate variability; (2) Electrodermal indicators that measure skin conductance, which can be affected by sweat; and (3) Energy Expenditure and skin temperature indicators. Among these indicators, Energy Expenditure (EE, kcal/min) is the most representative of psychological status, stress, and physical demands [2, 13]. Working at an EE rate that is above the maximum expected of a task results in decreased work productivity due to physical fatigue and a increased risk of work-related cardiac diseases and musculoskeletal disorders [24]. Therefore, field EE measurement is useful to assess workers' physical demands from ongoing construction tasks. However, the two accurate methods to measure EE (considering either the body heat loss or the oxygen consumption in performing a task) both are intrusive and interfere with workers' tasks [10, 31]. As such, EE must be approximated based on other parameters such weight, height, Heart Rate (HR), age, travel distance [16]. Fortunately, some studies have shown that HR, which is much easier to measure without hindering user's movements or actions, has a positive correlation with the level of physical exertion and EE measurement [3, 17, 20]. On the other hand, heart rate metric separately has also a strong positive correlation with the cardiac output, the level of physical exertion and cardiac diseases [22]. In the sports domain, therefore, HR has been used by coaches and athletes to monitor the level of fatigue [38]. Therefore, HR and approximate EE data have been adopted in this research to monitor construction workers' fatigue.

Recently, wristband-type wearable activity trackers have achieved a high level of sensing (e.g., accelerometer, HR sensor, etc.), real-time HR monitoring without hindering user's movements or actions (e.g., comfortable wristband-type), and affordability (e.g., less than $150 per unit). Most such trackers provide a user's EE during his/her free-living activities (e.g., walking and running) utilizing an algorithm combining embedded HR sensor data and previously identified HR-EE relationships for specific activities [13, 15, 27]. They mainly use a photoplethysmography (PPG) sensor for HR monitoring, however, the extraction of HR data from a wristband-type using PPG sensor during intensive physical activity remains challenging because of signals' contamination and distortions that come from workers' movements, sensor displacement, and environmental noises. Further investigation of using noise cancelation algorithms is required to test and improve the HR monitoring accuracy of wristband-type activity trackers, specifically for construction workers who perform intensive work [14, 33].

This research aims to facilitate the continuous monitoring and effective mitigation of workers' fatigue on construction sites. The research is proposing a framework that is designed for automated and near real-time data collection of workers' heart rate and energy expenditure using ubiquitous wrist wearables. Based on the monitored level of fatigue, the framework will suggest an efficient work-rest schedule that helps site works recover fast from fatigue, without hindering work productivity. As an initial stage in this research, this paper involves the following: (1) Selecting the suitable wristband-type activity tracker that can be used efficiently and enable easy access to health indicators of construction workers without requiring special facilities or equipment to collect data in the field; (2) developing a framework for automated real-time data collection of worker's features, location, heart rate, and estimated energy expenditure on an hourly basis using the selected wearable; and (3) discussing optional designs for work-rest schedules and the use of the collected data to facilitate this function.

2 Feasible Wearable Devices for Fatigue Monitoring

Location tracking has been the most common application offered by the construction-related systems that use advanced sensing and wearable devices to support construction safety and productivity. Applications such as ONSiteIQ use cameras and artificial intelligence software to identify workers, as well as potential safety hazards, such as workers without gloves, hats or proper fall protection. Although very beneficial, such special-purpose systems require a large investment to equip the site with the necessary infrastructure. Yet, their collected data may also not be suitable for identifying and mitigating the effect of fatigue on construction workers.

Because of their affordability, easy of use, and multiple features, the adoption of fitness-based wearable wristbands is gaining momentum in many industries, including construction. Fitness wristbands (e.g., Fitbit) can tell a person's pulse, GPS location, activity level, and even how well they have slept. With this information at the hands of site managers, workers who are feeling unwell can be pulled off for a checkup or assigned to light-duty until their biometric signs indicate they are able to do more intensive tasks [4]. A study conducted by Schall et al. [29] mentioned that 117 construction practitioners indicated that their organization would be willing to spend $63.17 U.S. per person for a wearable device. This suggests the potential of using ubiquitous technologies such as Apple watch, Fitbit, Garmin watch, and Kirdia band, or a construction version of these devices, to track workers' health and safety. In this study, therefore, the Fitbit wristband is selected to help monitor worker's overstress and fatigue based on heart rate readings. It is important to note, however, that all sensor-based wearable systems share some concerns related to privacy, interoperability, security, standardization, data safety, liability, and cost, which are being addressed as devices and systems evolve [19, 23].

3 Field Data Collection Using the Fitbit Wristband

Field HR and EE measurements enable practitioners to assess workers' physical effort in performing construction tasks [11, 26, 42]. In this paper, various models of Fitbit were investigated (e.g., Fitbit Ultra, Flex, Charge, Versa, Sense) to decide the most suitable for this research, considering cost, tracking metrics, accuracy, and being ubiquitous.

In terms of accuracy of HR measurements, Fitbit devices use PurePulse technology to measure HR based using a Photoplethysmography (PPG) sensor. A PPG sensor consists of a light transmits light with different wavelength into the individuals' tissue and a receiver receives the intensity of the reflected light. The intensity of the reflected light will be used to determine the change in blood volume over time [28]. All Fitbit models with PurePulse technology provide an acceptable HR accuracy, e.g., Stefanescu and Radoi [30] reported a good accuracy of Fitbit Charge 3 in collecting heart rate data in their real-world study to predict stress using wearables. In terms of EE measurement, Fitbit devices use accelerometers to estimate burnt calories, however, they were consistently unable to provide an accurate measure of EE in different test conditions [6, 7]. Therefore, in this research, the heart rate data will be used in analyzing fatigue, with the Fitbit Charge 3 model being selected to collect data from construction workers on an hourly basis.

Analysis of Fitbit Data Using Web API: Workers will be instructed to wear the Fitbit consistently Monday to Friday at work. Each Fitbit watch will be linked to a Fitbit account so that the physical activity could be accessed remotely. The Fitbit will be synced using the Fitbit app of each participant. Collected data of all workers is then transferred directly to a cloud service or to a personal device (mobile phone or laptop). Afterwards, analysis can be performed by granting access to third-party applications written by independent developers. Using Fitbit API, heart rate and calories burnt for the group of workers are written to an excel file every hour (e.g., Fig. 1). This file becomes ready to be read by the analysis mechanism that combines the collected workers' data with the project information about the nature of tasks and the work schedule (from the associated Microsoft Project file of the project) to assess the level of workers' fatigue and devise a mitigative action plan if the fatigue level is above a certain threshold level.

Laborers' Physiological information				Heart Rate Data					Energy expedenture data				
							Fitbit reading					Fitbit reading	
Labor ID	Gender	Age	Weight (BW in KG)	HR_{max} (beats/ min)	$HR_{max.A}$ (beats/ min)	HR rest (beats/ min)	$\overline{HR}$ morning shift (8 am to 12 pm)	$\overline{HR}$ morning shift (12 pm to 5 pm)	EE_{max} Kcal/min	MAEE Kcal/min	EE_{rest} Kcal/min	$\overline{EE}$ morning shift (8 am to 12 pm)	$\overline{EE}$ morning shift (12 pm to 5 pm)
1	M	40	74	160	144	56			11.98	4.50	1.86		
2	F	36	75	164	148	52			12.69	4.82	1.86		
3	M	29	69	171	154	52			12.57	4.86	1.86		
4	M	53	58	147	132	70			7.99	2.86	1.86		
5	F	45	78	155	140	50			11.90	4.40	1.86		
6	M	51	85	149	134	70			12.03	4.35	1.86		
7	M	33	67	167	150	50			11.71	4.49	1.86		

Fig. 1 Snapshot of workers' information spreadsheet

4 Fatigue Mitigation: Work-Rest Scheduling

Fatigue recovery can play a considerable role in the well-being and productivity of construction workers [41]. A lack of recovery can interfere with their productivity and also induce emotional, cognitive and behavioral disturbances, which can subsequently lead to increased risk of injuries and lack of productivity. However, sufficient rest can prevent the accumulation of fatigue and a loss of productivity. The impact of work exposure, including physical stress and mental stress, on productivity considered as "work decay". While, "Work-rest" is the time provided to recover from the work decay and help workers overcome the fatigue arising from the work [18]. When a break is given, the worker's performance is expected to increase due to recovery. The recovery value depends on how fatigued the worker is when the rest begins and the length of the rest [21]. Chan et al. (2012) conducted experiments on rebar workers in hot and humid environment and showed that a construction worker achieves 58% energetic recovery after a 5-min rest versus 92% after 30 min. Figure 2 illustrate the impact of rest time and frequency on workers recovery and productivity. In this figure, productivity decreases during work and recover during rest linearly as assumed by Bechtold and Thompson [1]. The figure shows four different cases: a full recovery break (as shown for worker W1, and W2) where the work rate at the beginning of the second work period is at its maximum; and a break that does not lead to full recovery (as shown for worker W3) where fatigue is accumulated during the second work period. However, worker W4 who observes frequent and brief rest breaks, has more productive time for two reasons: fatigue will not be increased as much, and the recovery will be better. As such, choosing between single rest-break or multiple intermediate short breaks (i.e. determining the number, place, and duration of workers' rest periods) is an important decision to accomplish project key deliverables. However, the problem of optimizing the work-rest schedule decisions is studied in different industry domains such as agriculture, nursing, manufacturing, with very limited efforts in construction. In work-rest scheduling literature, personalized variables of heart rate (HR), uptake (VO_2), energy expenditure (EE) were the most common health metrics correlated to fatigue and workload recovery [12, 21, 26, 35, 39]. These metrics increase continuously instead of reaching a steady state when a worker is engaged in a high-intensity work (e.g. construction) and increase the potential hazards and related problems [40].

The figure shows four different cases: a full recovery break (as shown for worker W1, and W2) where the work rate at the beginning of the second work period is at its maximum; and a break that does not lead to full recovery (as shown for worker W3) where fatigue is accumulated during the second work period. However, worker W4 who observes frequent and brief rest breaks, has more productive time for two reasons: fatigue will not be increased as much, and the recovery will be better. As such, choosing between single rest-break or multiple intermediate short breaks (i.e. determining the number, place, and duration of workers' rest periods) is an important decision to accomplish project key deliverables. However, the problem of optimizing

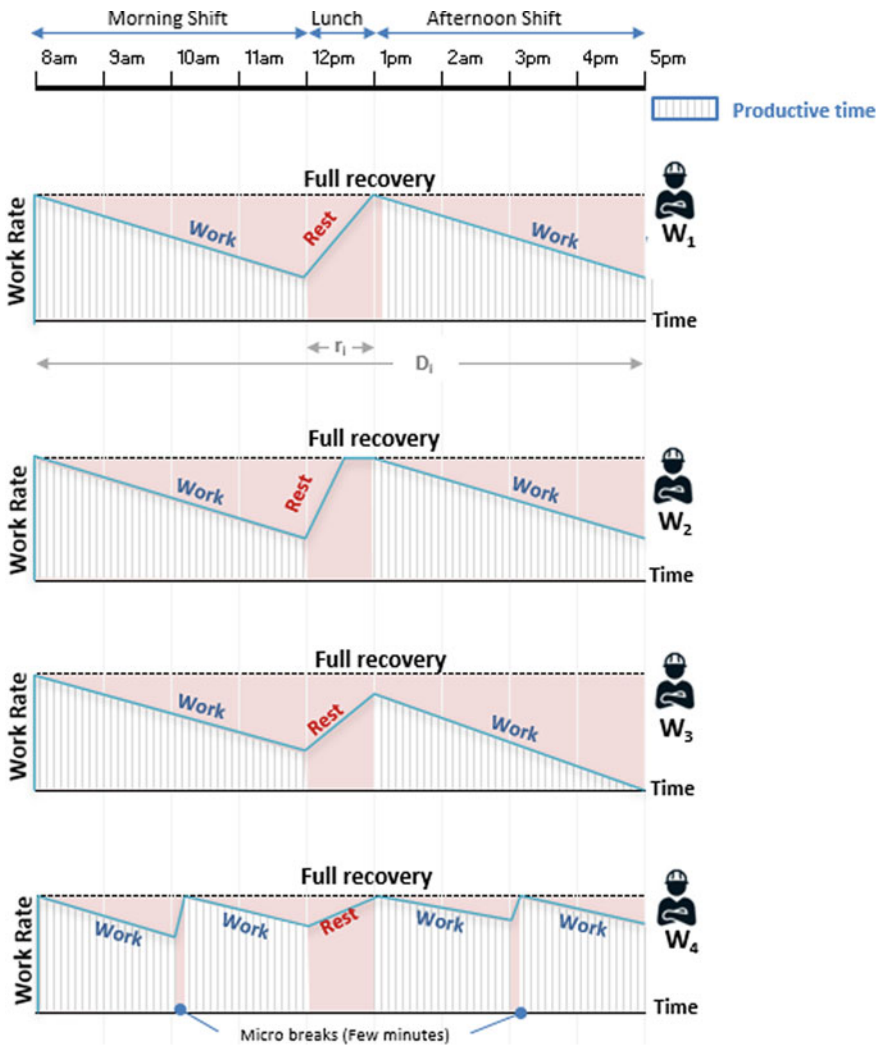

Fig. 2 Illustration of the impact of different rest schedules on fatigue recovery

the work-rest schedule decisions is studied in different industry domains such as agriculture, nursing, manufacturing, with very limited efforts in construction.

5 Proposed Work-Rest Scheduling

Existing efforts to schedule work rest adopted different objectives. Yi and Chan [41] maximized the total productive time of rebar workers by minimizing occurring

Table 1 Threshold of physiological metrics for different work intensity

Metric	Work intensity	Threshold
Heart rate (HR)	Rigours	>90% (200-age) for more than 5 min
	Moderate	<90% (200-age) and >50% (200-age)
	Low	<50% (200-age)
Maximum oxygen consumption ($\%VO_{2max}$)	Rigours	>85 ml/min/kg
	Moderate	<84 ml/min/kg and >50 ml/min/kg
	Low	<49 ml/min/kg
Energy expenditure (MET)	Rigours	>6 × the intensity of rest, usually 7–8 MET
	Moderate	<6 × the intensity of rest, and >3 × the intensity of rest
	Low	<3 × the intensity of rest, usually 4 MET

of heat stress in construction site, following a work-to-exhaustion then take-a-rest principle. Another effort by Ning et al. (2011) minimized the total cost considering costs of work stress with other direct monetary costs (wage costs, setup costs). Yi and Wang [42] optimized the work-rest schedule to minimize project duration and the physiological strain on the laborers considering equity and fair allocation between the laborers. However, these model are not supported by: the ability to measure physiological changes of workers while performing physical tasks in a timely manner and wihout interrupting the ongoing work, nor the mathematical representation of the relation between the productivity and provided breaks, was not included in their mathematical model.

To enable the calculation of workers' overexertion, rest allowance, and productivity loss, the level of work intensity in various tasks is classified as either Rigorous, Moderate, or Low, as defined in Table 1 [5, 36], depending on the values of various health metrics of: heart rate; maximal oxygen consumption, and energy expenditure.

The proposed framework is composed of two main components: (1) hourly-based Data gathering of workers' physiological features of heart rate, estimated energy expenditure data, and location; and (2) a mathematical work-rest scheduling for workers' assignment.

Inputs

For a project of n activities, each activity i (1 to N) input data are defined using parameters (d_i, m_i, $\overline{HR}_{i.work}$, $\overline{EE}_{i.work}$, $(P)_i$) which represent the working duration required by activity i, number of laborers required to perform activity i, average heart rate at work of all workers participating in activity i, average energy expenditure at work, and predecessors, respectively.

Worker (1 to J) are also defined by their physiological information and onsite tracked metrics (W_j, Y_j, G_j, ($HR_{j.max}$, $HR_{j.rest}$, $HR_{j.work}$), ($EE_{j.max}$, $EE_{.rest}$, $MAEE_j$, $EE_{j.work}$), (x1j, …, xij), (σ1j, σ2j, … σij)) which represent the worker weight, age, gender, maximum heart rate, heart rate at rest, average heart rate of the worker tracked from the Fitbit, maximum energy expenditure, energy expenditure at rest, maximum allowed energy expenditure, average energy expenditure of the worker tracked from the Fitbit, xij is a primary parameter that shows the initial assignment set to 1 if laborer j performs task i, and 0 otherwise; σij is a binary parameter that equals 1 if and only if laborer j is capable of performing activity i, and 0 otherwise; assuming that all laborers can perform all tasks (general laborers, unskilled workers), that is, all σij = 1.

Decisions

To determine an efficient daily work-rest schedule, the model has three variables:

1. Activity Scheduled Start: SS_i positive integer value $\forall$ i = 1, …, N
2. Activity modified duration: D_i positive integer value $\forall$ i = 1, …, N
3. Worker's reassignment variable: z_{ij} binary variable $z_{ij} \in \{0, 1\}$ $\forall$ i, j = 1, …, N.

Constraints

a. Individual maximum and acceptable limit of worker's fatigue in terms of heart rate and energy expenditure must be below the threshold limits and within the acceptable limits
b. Sum of the demands of a resource (j) by all eligible activities in each day (t, from day 1 to the end of all tasks) must be within the resource availability limit.
c. Precedence relations between tasks must be respected. Where, the scheduled finish time (SF_i) of an activity i is the sum of the scheduled start time (SS_i) plus activity duration (d_i) considering the productivity loss due to workers energy exertion, i.e., ($SF_i = SS_i + d_i / P_i$).

Objective Functions

The objective function of the proposed model has two components: (1) Minimizing project duration by maximizing the total productive time; and (2) safeguarding the health and safety of construction workers by maximizing the minimum difference between the energy expenditure at work value and the acceptable/threshold of energy expenditure. These objectives by turn should indirectly affect the cost of the project by decreasing the cost of pausing from work, and cost due to increased risk of injury caused by keeping certain level of physiological stresses, respectively. With all of the above considerations regarding the tasks and the laborers, the team leader assigns the tasks to the laborers with the aim of minimizing the job completion time and the total extra energy expenditure of the laborers. Based on the decision variables and basic constraints, two main expressions have been represented in the model (Total Project Duration; and Total energy expenditure) to be used individually or combined as an objective function. In case of minimizing Total Project Cost, an additional constraint is needed to restrict the Project Duration to the deadline. The team leader of the laborers, when assigning the tasks, also needs to take equity into consideration: the total work load of two laborers should not differ too much. As the model has two objectives, an overall objective function is the weighted sum of both objectives, with the values of the weights determined according to the project managers' preferences.

6 Conclusions

In construction, the classical scheduling algorithm, ignores constraints related to a human's physiological factors and limitations, resulting in unrealistic schedules. This paper is proposing a framework for unobtrusive monitoring of the physiological changes of workers' during their work performance, and then accordingly setup activities times, and associated rest duration, select optimal task performance sequence, and reassign at-risk workers. Ongoing efforts (almost completed) develop a new mathematical formulation of construction schedule on daily basis that understands human personal demands, and code it using the powerful constraint programing tool of the IBM ILOG CPLEX Optimization Studio 12.8. Future work will examine the performance of the model on real-size construction projects. To the author knowledge, this study is the first effort to consider the real-time physiological condition of workers while determining the number and timing of breaks and workers assignment that are currently missing in existing practices.

Acknowledgements The work presented in this paper was funded by University of Waterloo Interdisciplinary Trailblazer Fund.

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An Integrated AHP-TOPSIS Methodology for Selecting Suitable Project Delivery Method for Construction Projects

N. Soltanikarbaschi and A. Hammad

1 Introduction

A project delivery method (PDM) can be defined as: "*system for organizing and financing design, construction, operations, and maintenance activities that facilitates the delivery of a good or service*" [13]. Selecting an appropriate PDM that meets the project's requirements and the owner's needs is a critical task that can profoundly influence the efficiency of the project execution process. As an example, it has been estimated that the selection of an appropriate PDM can reduce construction project costs by an average of 5% [4]. In many cases, however, the decision about the PDM is often made intuitively and based on unstructured approaches [5], which can result in an inappropriate project delivery strategy and failure of the project. Hence, selection of the PDM should be based on a structured analytical approach. There are several PDMs that owners can choose from. In this research, three project delivery methods are considered: design-bid-build (DBB), construction management at risk (CMR), and design-build (DB). Each PDM has its own advantages and disadvantages. However, there is no PDM that is universally the best for all projects. A PDM that leads to the success of one project can result in failure of a project under different circumstances.

DBB is usually referred to as "the traditional method" in which the owner contracts with a designer to conduct the preliminary and detailed designs for the project. Thereafter, the owner advertises and calls for bids, and they award a separate contract to the best bidder for construction of the project based on the designer's completed construction documents. This selection is typically based on the lowest price. In

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S. Walbridge et al. (eds.), *Proceedings of the Canadian Society of Civil Engineering Annual Conference 2021*, Lecture Notes in Civil Engineering 247,
https://doi.org/10.1007/978-981-19-0968-9_48

DBB, the owner is financially liable for the cost of any design errors, omissions, or changes faced in the construction phase [9]. This delivery method involves sequential separate phases, and the construction phase cannot begin until all design and procurement phases are complete. Thus, it may lead to a longer project duration as compared to other delivery methods and has the potential to foster adversarial relationships between involved parties [11]. CMR is a delivery method in which the owner engages a competent contractor who is then committed for the construction performance and the risk of delivering the project within a defined schedule and price. In addition, the owner contracts a designer to provide design services [9]. DB is a delivery method in which the owner procures both design and construction services from a single, legal party referred to as the “Design-Builder”. This delivery method allows the overlap of the design and construction phases, resulting in opportunities for innovation and improved constructability [15]. This approach can eliminate the adversarial relationship in DBB because one entity is responsible for both the design and the construction. It can also reduce the overall time of project completion [1] and, as a result, it is generally used for fast-track projects.

2 Background and Problem Statement

Various studies have proposed methodologies and techniques for selecting an appropriate PDM for a project. Alhazmi and McCaffer [3] conducted research on a selection model for project procurement system, and they applied Parker’s judging alternative technique in their proposed model. This methodology contains four screening stages including feasibility ranking, evaluation by comparison, weighted evaluation and the analytical hierarchy process (AHP). In this study, four main criteria of time, cost, quality, and owner’s general needs and 25 sub-criteria are considered as selection factors in the procurement selection process. A major problem associated with this study is considering contracting methods and delivery methods at the same time as potential alternatives. For example, “construction management” and “cost reimbursable contracts” cannot be compared with each other as delivery method alternatives. Chan et al. [6] conducted a study on proposing a model for procurement system in construction projects using multivariate analysis through applying Delphi survey technique. In this proposed technique, a selected expert panel was asked to answer four questionnaires about influential factors in the selection of the procurement system in construction industry. This approach is extremely time consuming, and the authors mentioned that some experts did not provide their responses through all rounds of Delphi process. Al Khalil [1] and Mahdi and Alreshaid [14] used AHP for the selection process. Al Khalil states that since AHP approach can consider both tangible and intangible factors in the analysis process, it can be a useful tool for the owners to select the appropriate PDM. Al Khalil [1] considered 12 influencing factors, while. Mahdi and Alreshaid [14] considered 34. A shortcoming of these studies that when owner’s preference comparisons among criteria change, the ranking weights of the criteria would remain relatively unchanged due to the large number of influencing criteria. Oyetunji and Anderson [18] proposed a decision-making approach in which quantitative relative effectiveness values were generated for PDM selection, and then they used these values in the simple multi attribute rating technique (SMART) methodology for the selection of appropriate PDM. They considered 12 project delivery alternatives, and these alternatives are a combination of PDMs and contracting and payment methods, which are not comparable. Moreover, this model considers 20 factors as critical selection criteria which have been given predetermined weights. Mostafavi and Karamouz [16] used a fuzzy, multi-attribute decision making approach in which they considered 20 critical selection criteria. In this study, the attributes' weights are determined by the decision maker linguistically, which does not provide a comprehensive prioritization of the attributes. Chen et al. [7] developed a PDM selection model with data envelopment analysis (DEA)-bound variable (BND) and Artificial Neural Networks (ANN). Sixteen indicators are proposed as selection criteria, which are categorized into four groups of project objectives, project characteristics, characteristics of owner, and characteristics of contractor and external environment. The proposed method includes DB and DBB delivery methods, and it includes three stages. In the first stage, the decision maker needs to establish a database containing enough data from similar projects. This step can be very time consuming or might not be feasible due to lack of access to similar project data. In the second step, indicator values are examined. The final step is training the modified similar projects' data through which the proper PDM would be predicted.

There are some limitations that are shared among the existing PDM selection approaches. First, because some studies considered many selection factors, the ranking of the attributes remain relatively unchanged when the owner's preferences change. In addition, other studies did not consider a systematic approach for obtaining attributes' weights; in a number of studies, predetermined weights were used in the PDM selection approach, losing consistency in the judgments. Finally, the implementation of some selection approaches is highly complex, time consuming, and may not be generalizable. These limitations have inspired this study that proposes a systematic selection framework ranks of criteria in a structured manner and is easy to use.

3 Methodology

The conceptual model of the proposed framework is shown in Fig. 1. The model was developed considering three main components: PDM selection criteria, deriving weights of criteria using AHP, and ranking PDM alternatives using the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS).

First, applicable PDM selection criteria for construction projects was obtained from the literature. Then, AHP was applied for deriving selection criteria weights based on the owner's needs and preferences. In this step, the owner of a project is asked to conduct a pairwise comparison between selection criteria. The owner's

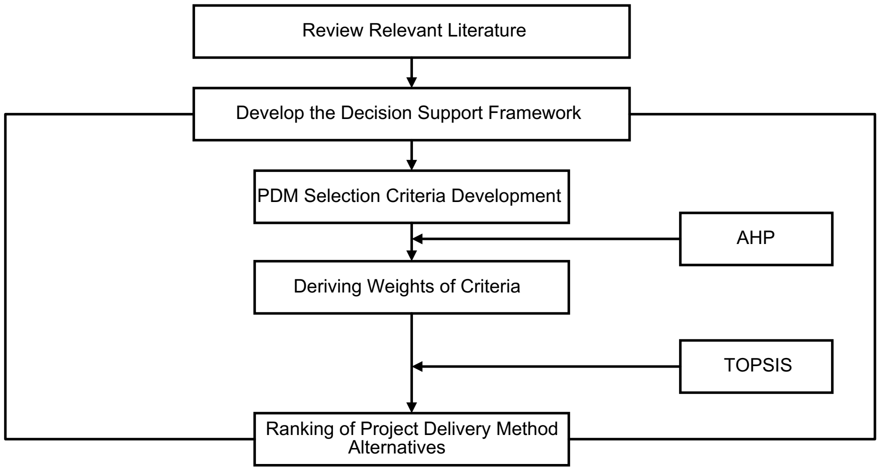

Fig. 1 Conceptual model of proposed framework

Table 1 The AHP comparison scale given by Vargas [23]

Weight	Definition
1	Equal importance
3	Weak importance of one over another
5	Essential or strong importance
7	Very strong importance
9	Absolute importance
2, 4, 6, 8	Intermediate values between the two adjacent judgments
Reciprocals of above	If factor i is assigned one of the above numbers, then j has the reciprocal value of i

preferences will be presented based on a scale of 1–9 (Table 1), as described by Vargas [23].

Once the criteria weights were assigned, TOPSIS was used for ranking PDM alternatives. Overall, this framework was developed for decision makers in construction industry.

3.1 *Development of Selection Criteria*

Various surveys have been conducted to find the factors that affect PDM selection the most. Table 2 summarizes several of proposed selection criteria from the chosen reference. Several proposed factors have similar meanings, but different expressions were used for them. To unify the concepts, one expression form was selected for each

Table 2 Critical criteria for PDM selection proposed in the literature

Selection criteria	References[a]									
	A	B	C	D	E	F	G	H	I	J
Schedule	Δ	Δ	Δ	Δ	Δ	Δ	Δ	Δ	Δ	Δ
Cost	Δ	Δ	Δ	Δ	Δ	Δ	Δ	Δ	Δ	Δ
Quality	Δ		Δ			Δ	Δ			Δ
Site conditions									Δ	Δ
Familiarity and establishment					Δ	Δ				
Innovation		Δ						Δ		
Owner's experience and capacity					Δ	Δ	Δ	Δ	Δ	Δ
Regulations and policies					Δ	Δ	Δ			Δ
Project complexity		Δ	Δ	Δ	Δ	Δ	Δ	Δ	Δ	Δ
Market conditions									Δ	Δ
Flexibility for changes			Δ	Δ	Δ	Δ	Δ		Δ	Δ
Clarity of project scope				Δ	Δ	Δ				
Uncertainty			Δ		Δ				Δ	
Conflict of interest			Δ			Δ				
Risk management		Δ	Δ		Δ	Δ	Δ	Δ		Δ
Allowance for competitive bidding					Δ	Δ		Δ		
Design				Δ		Δ		Δ		

[a]Note: A = Konchar and Sanvido [12], B = Oyetunji and Anderson [19], C =Cheung et al. [5], D = Al Khalil [1], E = Chan et al. [6], F = Mahdi and Alreshaid [15], G = Mafakheri et al. [18], H = Tran et al. [22], I = Yoon et al. [24], J = Ding et al. [10]

of those factors. The most common PDM selection factors that are considered in this study are schedule, cost, quality, project complexity, flexibility to change, owner's experience and capacity, and risk management. Furthermore, as the number of selection factors increases, the assigned weights become more similar, and the model is less sensitive to the owner's preferences for prioritizing the criteria. Therefore, while selecting effective variables, the individual factors were chosen for a manageable number of variables.

3.2 *Obtaining Critical Factors' Weights Employing AHP*

AHP helps a decision maker divide a complex problem into smaller elements and develop a hierarchy of elements [19]. These elements include criteria and feasible alternatives. Then, the evaluation process proceeds through a pairwise comparison between criteria, and all evaluation ratios are combined to obtain an overall rating of the alternatives. The steps of AHP are:

Table 3 Ratio index value for matrixes with different size

Size of matrix	2	3	4	5	6	7	8	9	10
RI	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49

1. Select criteria that should be ranked according to the owner's preferences.
2. Develop a comparison matrix, quantify the selected criteria through pairwise comparison, and generate weights using a rating scale.
3. Normalize the resulting matrix by summing each column and dividing each value by the sum of the corresponding column. The result is the normalized value of each element. The corresponding factor's weight is then calculated by the average in each row.
4. Calculate and check the consistency ratio. In some cases, the comparison matrix is inconsistent for a couple of reasons. First, the decision maker is unable to do the pairwise comparison consistently. Second, the method itself has inherent inconsistency due to using fixed values while comparing the pairs [21].

To check the consistency of the matrix, a consistency index (CI) is calculated and compared with a fixed value of random index (RI) [20].

$$CI = (\lambda_{max} - n)/(n - 1) \quad (1)$$

where n is the matrix size. The value of λ_{max} is determined by adding the normalized values of all elements in each column, multiplying the resulting sum of each column by the corresponding relative priority value (weight), and adding the results of the relative multiplications.

The RI is shown in Table 3, and the consistency ratio (CR) is calculated as [2, 12]:

$$CR = CI/RI \quad (2)$$

Any matrix with a CR below 0.10 is usually considered acceptable because this level of inconsistency does not severely affect results [2].

3.3 *Using TOPSIS Approach*

After obtaining criteria weights from AHP, then TOPSIS method ranks PDM. TOPSIS method is developed by Chen and Hwang [8]. It relies on defining the alternative that has the shortest distance from the positive ideal solution (PIS) and the farthest distance from the negative-ideal solution (NIS). As per the authors, the TOPSIS procedure consists of the following steps:

Step 1. Obtain the normalized decision matrix. The normalized value r_{ij} is calculated as:

$$r_{ij} = f_{ij} / \sqrt{\sum_{i=1}^{n} f_{ij}^2}, \quad j = 1, \ldots, J; \quad i = 1, \ldots, n, \tag{3}$$

where f_{ij} is the ranking of alternative i with regards to criterion j.

Step 2. Modify the obtained matrix using the weight of each criterion. The weighted normalized value v_{ij} is calculated as:

$$v_{ij} = w_j.r_{ij}, \quad j = 1, \ldots, J; \quad i = 1, \ldots, n, \tag{4}$$

where w_j is the weight of the jth criterion, and $\sum_{j=1}^{j} w_j = 1$.

Step 3. Define the PIS (A^+) and NIS (A^-).

$$A^+ = \{v_1^*, \ldots, v_n^*\} = \{(\max v_{ij} | j \in I'), (\min v_{ij} | j \in I'')\}, \quad j = 1, \ldots, n \tag{5}$$

$$A^- = \{v_1^-, \ldots, v_n^-\} = \{(\min v_{ij} | j \in I'), (\max v_{ij} | j \in I'')\}, \quad j = 1, \ldots, n \tag{6}$$

Step 4. Utilize Euclidean distance to determine the separation of each alternative from the PIS and NIS:

$$d_i^+ = \sqrt{\sum_{j=1}^{n} (v_{ij} - v_j^+)^2}, \quad i = 1, \ldots, n \tag{7}$$

$$d_i^- = \sqrt{\sum_{j=1}^{n} (v_{ij} - v_j^-)^2}, \quad i = 1, \ldots, n \tag{8}$$

Step 5. Determine the relative closeness for each alternative i with respect to A^+:

$$cl_i^+ = \frac{d_i^-}{d_i^+ + d_i^-}, \quad i = 1, \ldots, n \tag{9}$$

Step 6. Rank all alternatives according to relative closeness.

The alternative with the highest rank represents the optimum solution.

Table 4 Decision matrix for PDM selection[a]

PDM	Criteria						
	Schedule	Cost	Quality	Complexity	Flexibility to change	Owner's experience and capacity	Risk management
DBB	1	9	5	5	1	5	3
DB	9	3	9	1	9	5	5
CMR	5	5	7	5	9	9	9

[a]Linguistic terms for rating scales: 1 = poorly effective, 3 = ineffective, 5 = fairly (neutral) effective, 7 = effective, 9 = highly effective

4 Results and Sensitivity Analysis

4.1 Decision Matrix for PDM Selection

Table 4 shows the PDM decision matrix in which different possible alternatives are compared and are given rating scores according to different criteria. In this study, the rating scale ranges from 1 to 9.

4.2 Hypothetical Case Study

The framework proposed in this study was implemented on a hypothetical case study. For this project, 1 the most important goal was compressing the project schedule. Therefore, the owner assigned the highest-ranking to "schedule" in comparison with the other selection factors. As such, Table 5 indicates criteria pairwise comparison matrix with respect to the project's top goal, the schedule, and Table 6 shows criteria weights for the schedule-driven project obtained through AHP process.

Since the CR is less than 0.1, the pairwise comparison matrix is consistent. Having criteria weights, TOPSIS methodology was implemented. Tables 7, 8 and 9 show the calculated distance from ideal solution (d_i^+), distance from negative-ideal solution (d_i^-), and alternatives' relative closeness to ideal solution (cl_i^+), respectively.

The higher the value of cl_i^+, the higher the ranking of the alternative. Therefore, for the hypothetical, schedule-driven project, DB should be selected since it has the highest value of relative closeness to ideal solution.

A sensitivity analysis was also carried out to study the impact of different criteria on PDM selection. For this purpose, it was assumed that the studied critical factor has the highest weight in comparison to other criteria in each iteration. Therefore, in the pairwise criteria comparison matrix, the studied factor is given score 9, while all other criteria get the lowest ranking point. Table 10 contains the results of this sensitivity analysis, indicating which project delivery method would be most suitable if the highest priority changes. As can be seen, if the owner decides to consider "flexibility",

Table 5 Criteria pairwise comparison matrix with respect to the project's top goal

Criteria	Schedule	Cost	Quality	Complexity	Flexibility to change	Owner's experience and capacity	Risk management
Schedule	1	9	9	9	9	9	9
Cost	0.111	1	1	1	1	1	1
Quality	0.111	1	1	1	1	1	1
Complexity	0.111	1	1	1	1	1	1
Flexibility to change	0.111	1	1	1	1	1	1
Owner's Experience and capacity	0.111	1	1	1	1	1	1
Risk management	0.111	1	1	1	1	1	1

Consistency ratio = 0

Table 6 Criteria weights for the schedule driven project obtained through AHP process

Criteria	Schedule	Cost	Quality	Complexity	Flexibility to change	Owner's experience and capacity	Risk management
Weight	0.6	0.0667	0.0667	0.0667	0.0667	0.0667	0.0667

Table 7 Distance from ideal alternative

PDM	DBB	DB	CMR
d_i^+	4.71664	0.7679	3.28533

Table 8 Distance from negative ideal alternative

PDM	DBB	DB	CMR
d_i^-	0.50054	4.68055	1.58794

"complexity", "owner's in-house experience and capacity" or "risk management" as the most significant goal of the project, CMR would be the most appropriate PDM. If the owner chooses "schedule" or "quality" as the most important factor, the DB would be chosen as the most suitable PDM. If "cost" is considered as the highest priority, the results reveal that DBB would be the most suitable PDM.

Table 9 Relative closeness to ideal solution

PDM	DBB	DB	CMR
cl_i^+	0.09594	0.85906	0.32585

Table 10 Sensitivity analysis results

Studied critical criterion	Considering the studied factor as the top goal of the project (relative weights change accordingly)	PDM selected by the proposed framework
Schedule	Studied factor's weight is 60% and the other criteria weights are approximately 6.6%	DB
Cost	Studied factor's weight is 60% and the other criteria weights are approximately 6.6%	DBB
Flexibility to change	Studied factor's weight is 60% and the other criteria weights are approximately 6.6%	CMR
Project complexity	Studied factor's weight is 60% and the other criteria weights are approximately 6.6%	CMR
Quality	Studied factor's weight is 60% and the other criteria weights are approximately 6.6%	DB
Owner's experience and capacity	Studied factor's weight is 60% and the other criteria weights are approximately 6.6%	CMR
Risk management	Studied factor's weight is 60% and the other criteria weights are approximately 6.6%	CMR

5 Conclusions

This study provides a systematic, structured methodology for construction projects owners to select the most suitable PDM for their projects. The delivery system that is selected should be able to help the owners achieve the project goals and objectives in an efficient, cost-effective manner. This study developed a list of critical factors that affect the selection of PDM. The proposed decision support framework enables the owners to assess the importance of each factor with regards to their project, assign weights to these factors in a comprehensive and systematic way, and evaluate the potential alternatives to select a PDM that facilitates the project's goals.

A sensitivity analysis was conducted to determine how the results of this framework change when it is applied to projects with different top priorities. The PDM selection approach in this study was developed based on characteristics of construction projects in which the available alternatives and effective criteria have been considered. Therefore, the scope of this research was limited to construction projects, and it the proposed system may not be applicable for other types of project as well. Hence, a recommendation for future research efforts would be to develop a systematic PDM selection approach for other types of projects with specific characteristics.

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Innovation and Effectiveness Through Diversity

Peter Calcetas and Brianna Murree

1 Introduction

A workplace where diversity is present benefits all levels of the organization including individuals, team/group dynamics, vendors and suppliers. In the context of this case study, the term ‘diversity’ consists of members of varying age, gender, culture, ethnicity, language, and place of origin. As team members have varying backgrounds, talents, and abilities, the organization is able to gain unique perspectives when solving complex problems which, in turn, leads to increased employee engagement, productivity, and a greater competitive advantage.

Although the concept of a diverse work environment remains ideal for organizations, achieving organizational efficiency and cohesion through diversity and inclusion does not come without short-term challenges. The difficulty of achieving team cohesion through diversity requires team members to not only self-reflect on individually but reflect upon others to reach common ground and understanding. Thus, reaching a common understanding among a group of diverse individuals is what is referred to as ‘normalizing cognitive bias’. As normalization requires a framework, this case study’s target organization, HKC Construction (“the Organization”) combines the fundamental building blocks of technologies, training, leadership, and mentorship to achieve synchronicity and overall team cohesion in the industries of Architecture, Engineering and Construction (AEC). Adapted by the author, Peter Calcetas, the frameworks in relation to an individual (see Fig. 1), are key to understanding each individual’s diverse characteristics and behaviors before building towards organizational efficiency and team cohesion. The analysis framework developed for this case study utilizes four perspectives to observe the individual

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S. Walbridge et al. (eds.), *Proceedings of the Canadian Society of Civil Engineering Annual Conference 2021*, Lecture Notes in Civil Engineering 247,
https://doi.org/10.1007/978-981-19-0968-9_49

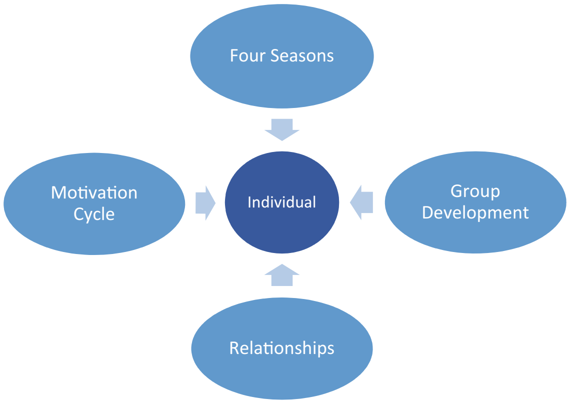


Fig. 1 Frameworks in relation to analyzing individual's behavior

team members, specifically: Four Seasons, Group Development, Relationships and Motivation Cycle.

2 The Organization's Case of "Four Seasons"

The Four Seasons perspective compares the individual's experience living and working in a part of the world that has relatively different season change and compared this to the team member's earlier experiences. For the Organization, the experience of its team members in the AEC (Architecture, Engineering, Construction) sector varies by city and country of origin, education, discipline, and age group. In this case, the workforce includes visible minorities (29%), employees that have immigrated from outside of Canada (50%), and are bilingual—Spanish, Portuguese, Greek, French, Dinka, Filipino, Arabic, Italian (99.1%). Therefore, for many on the team, the broader temperature range and four seasons come with personal challenges, as different standards are implemented for each country. The change of seasons from autumn to winter caught many newcomers ill prepared to the nuances of construction.

In this case, half of the members on the Organization's team, cold weather concreting was not a consideration for project scope, timeline, or budget. Their prior experiences did not encompass the issue of cement hydration in low temperature. The phenomenon of cold weather concreting was not a factor for quality. Many of our members came from warm weather experiences, where the higher ambient temperatures contributed to accelerated hydration. To help bring the entire team to a mutual understanding of quality control for concrete during cold weather, the Organization delivered orientation classes intended to be refresher courses for some, and new knowledge for others. The questions posed during the in-house education were the seeds of valuable unintended consequences. The Organization was inspired to adopt advanced techniques and technologies as a complement to the local Canadian best practices. Addressing the needs of the entire team in an open, safe, and non-judgmental manner, removed assumptions from the equation. This allowed the entire Organization's local grown experts and expatriates alike to view the issue at hand with fresh eyes. This fresh eye approach encouraged the deployment of a much-improved operating procedure which mitigated risk more effectively, while increasing productivity.

What was experienced is known as the "Commitment Effect", which is a cognitive decision-making bias that skews problem solving and decision making. The benefit of having teammates that are not committed to the typical way of solving problems or following processes without reconsidering the context of each situation. This prompts the question, "How do we avoid what is known as 'the Sunk Cost Fallacy'"? Julia Galef, President at the Center for Applied Rationality proposes a concept "Rationality in Action: Look at a Problem as an outsider" [1]. By using the case situation as a multi-culture, multi-country of origin collective of teammates, the organization has access to "Looking at a problem as an outsider" by virtue of team composition.

Initially, the construction progress did seem as if the team were off to a slow start for the cold weather concreting issue if it were not for a more patient and sympathetic approach incorporating a strong desire for inclusiveness. The altruistic motivation to mentor and guide members less familiar with local conditions, dynamics, and restraints forced more well-versed team members to reconsider typical standard operating procedures. In other words, it was the effort of articulating a phenomenon and its treatise which allowed the expert on the team the opportunity to consider the situation like an outsider. The thought exercise created opportunities for profound insight which propelled the action of retuning the process by incorporation a fusion of time-honored techniques for cold weather concreting such as, insulation, space heating and tenting, in concert with wireless sensors, cloud computing, artificial intelligence and the Nurse-Saul Theory of concrete maturity [2]. In the construction sector, where time is at a premium, competing with project budget and scope, it is doubtful that people would invest the effort and time dedicated toward introspection. In this case, diversity was the seed of innovation and the spark for action.

3 Team Dynamics: Diversity Versus Normalization

The Theory of Team Dynamics: Individuals are free to act in service to their own needs and desires. In effect the person's means are directed toward their desired end results. A group of individuals who continue to act solely in their own interests, simply share the same space and continue to act with their own means toward their individual ends. When the individuals begin to interact toward a common goal or goals their means (resources), needs and desires (end results) become interdependent. This interdependency is highly productive when means/resources, actions and end goals/results are coordinated. The stages of team dynamics and small group development, according to Bruce Tuckman, noted behaviorist, have been observed to be composed of the following stages: [1] Forming, [2] Storming, [3] Norming, [4] Performing and [5] Adjourning [3].

As a team, the Organization was quite diverse from a country of origin and primary language perspective. All members speak at least two languages fluently. The education and experiences were also diverse, spanning three continents and a dozen countries. After the team's Forming stage, characterized by a period of friendly tentative relations and moderate productivity, the change of seasons revealed the relevant experience and educational compatibility with local conditions. Evidently, there was a large discrepancy with four season experiences. The consequences of the out of sync skills and experience sets was the trigger for an intense Storming stage. At this point, the concern was the erosion of team cohesion.

3.1 The Basis of Relationships

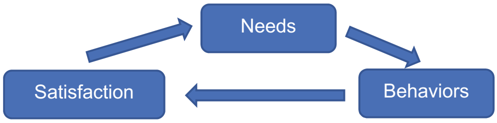
Relationships are built on three primary components: [1] mutual trust, [2] mutual respect and [3] the willingness to adapt. Assigning blame and isolating individuals or groups is a symptom of a reduction in mutual trust and mutual respect. To change the trajectory of the team dynamic, senior management quickly intervened by leveraging [3] the willingness to adapt. With such a diverse group, each team member was comfortable with adaptation since they each had a multi-cultural life experience. Negotiating the differences between cultures was a learned adaptive skill and expectation. To drive normalization, a knowledge exchange program of local best practices and technical fundamentals was given to all members through in-house lecture and 1 on 1 tutorials. Hands on training, experiential learning and theoretical discussions resulted in an increase of [2] mutual respect which quickly led to the repair of [1] mutual trust. The high level of adaptation amongst the team greatly facilitated normalization which accelerated quickly to the Performing stage of team dynamics.

By the beginning of the winter season, the team collectively concluded that they were equally comfortable performing in the cold weather phases of the year and look forward to similar knowledge exchange in anticipation of the warmer spring and summer seasons ahead. The diverse experiences created an intense and turbulent Storming stage of team dynamics. However, the diversity also increased the general willingness to adapt which, coupled with an understanding of the foundational principle of relationships, facilitated a quick normalization stage and accelerated to the performing stage. In retrospect, diversity was the seed of increased performance.

3.2 Individual Motivation

Organizational behaviorists explore the concept of motivation. At a fundamental level, individual motivation is an evolving cycle of (1) Needs, (2) Behaviors and (3) Satisfaction (see Fig. 2). From the individual's perspective, the starting point is the identification of Needs which are defined, followed by a determination of a potential

Fig. 2 Individuals' motivation cycle



solution through Behaviors, based offering of service effectively leveraging their skills, then the Needs reach a level of Satisfaction. It is this ongoing cycle that drives individual motivation, and as the needs evolve, so too will the Behaviors.

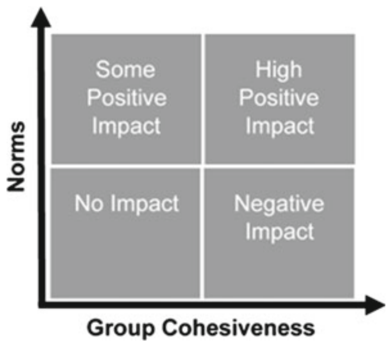
To aid in the understanding this dynamic in the context of work, motivation can be understood using two different perspectives: Content and Process of Motivation. Content Motivation seek to explain an individual or group of individual's actions to satisfy needs and aspirations [4]. In short, Content Motivation is focused on what motivates the individual. The Process Motivation perspective explores the potential reason how and why motivations affect individual behavior, which is effectively how motivation occurs within the person's decision criteria [5].

3.3 Content Motivation and the Four Seasons

When observing the Storming stage of the case study, the Content Motivation theory that is particularly relevant is offered by Elton Mayo—where norms and group cohesiveness aid in explaining the intensity of the Storming stage and the transition to Norming and Performing.

The Mayo Theory of Motivation created by Elton Mayo (Fig. 3) helps to explain what was motivating individual team members leading up to the "Four Seasons" Case. Initially, the team exhibited a low level of Norming with a moderate level of group cohesiveness, partly due to the relatively newness of the team members, where ½ the team joined less than 6 months earlier but buttressed by the extend family nature of the organizational culture.

Fig. 3 The Mayo theory of motivation [6]



3.4 Process Motivation and the Four Seasons

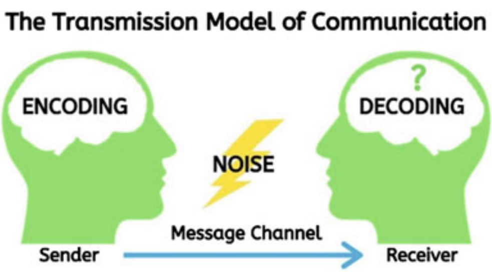
When considering the Process Motivation to explain HOW motivation occurs, the Equity Model is one of the more appropriate frameworks. Equity, as the title implies, is the balance between the inputs the individual receives and the outputs the individual supplies. It has been observed that some members of the team interpreted performance to be lower than their expectations. This gave rise to feelings of tension due to the inequity of the division of labor and resulted in dispute, which contributed to the Storming stage of team dynamics.

3.5 Communication and Diversity

Personal communications do impact how individuals behave. According to the PMI (Project Management Institute) training for the PMP (Project Management Professional) communication is subject to three errors: (1) Encoding, from the message Sender, (2) Transmission, the medium used to send the message and (3) Decoding, by the Receiver [7]. For visual reference, refer to Fig. 4: Transmission Model of Communication [8]. The Encoding is influenced by the Sender and is linked to their life experiences, culture, personality, and temperament among many other factors. In the case of a remarkably diverse team, the Encoding phase is not normalized with a new team. Similarly, to Encoding, the Decoding errors are equally valid and affected by the individual's attributes. In the interests of efficiency, we will simply acknowledge that Transmission errors have and will continue to occur in a manner and frequency consistent with organizations conducting business in the Canadian economy.

The phenomenon of communication errors that were observed was particularly extreme and exacerbated by cultural differences. One example which repeated itself, except for intervention, was when an Encoder came from a culture which was very direct in their communication with no emotional investment in the content or consequence of the interpretation; and Transmitted the communication to a Decoder from a culture which attached social standing and the perception of performance in communications. Often, the unintended consequences were a misinterpretation. The Encoder

Fig. 4 Transmission model of communication [8]



was intending to communicate, in this case, a specific situation. The Decoder interpreted this as a professional disparagement. The opportunity to normalize, through the various trials the team overcame, was the impetus to profoundly explore practical alternative solutions available to the team. The patience and effort needed to overcome the challenges required a much higher commitment of time, research, and communication to normalize all the members in technical knowledge, methods and means of communication. The increased difficulty in communication motivated the team to seek and adopt techniques and technologies to reduce barriers to effectiveness. Collaborative SaaS (Software as a Service) aided the Encoding and Decoding errors with the added benefit of also reducing Transmission errors. Further, the drive to facilitate effectiveness also created a "gateway" solution to adopt other technologies like wireless concrete maturity sensors, cloud computing, artificial intelligence, and predictive modeling.

As an observation, the elevated level of diversity contributed to a much more challenging and intensive Storming stage. However, with a high willingness to adapt, patience and perseverance, the consequences are a higher individual and team effectiveness, technical adoption, and search for practical applications of innovation.

4 Conclusion and Observations

Diversity in the context of a For Profit Enterprise in the Canadian AEC Sector is a consequence of the multi-ethnic social make up of Canada. This situation presents a heightened communication and cultural barrier beyond the existing generational differences that exist in a mono-ethnic society. The team, in this case, utilized the three pillars of healthy relationships: mutual trust, mutual respect, and the willingness to adapt as a base to create Team Cohesion, productivity and a self-styled "Social Contract" to interact.

At the group level, normalizing cognitive bias through understanding diversity and incorporating an organizational framework consisting of innovative technologies, training, and hands on mentorship, organizations can effectively improve employee engagement, productivity, and organizational efficiency.

At the individual level, the team members became normalized to a mutually acceptable manner of articulating, through considerate Encoding, not only the information but also the context of the message in a manner which emphasizes facts-based language and phrasing. This has been found to mitigate the risk of Decoding errors by reducing the likelihood of crossing a cultural threshold of individual character judgment.

To journey as part of a team composed of diverse individuals is a greater challenge. To choose a path which respects the differences in the storming stage and incorporate the opportunity to drive normalization with consideration, research, collaboration, and innovation may, as in this case, bear the fruits of higher productivity and team cohesion. We are inspired by the sentiment of the French Culture which celebrates, "*Vive la différence!*".

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Life-Cycle Analysis for Upgrading Residential Buildings to Optimize Energy Consumption

M. Sandhu and M. R. Dann

1 Introduction

Houses provide an essential aspect for humanity—shelter. The elements of the outer building envelope play an important role in maintaining the temperature inside a house. Modifying these elements can change the energy consumption of the house and reduce the cost of energy in the long term. 39 percent of energy-related carbon dioxide emissions are from buildings and construction—that is 125 Exajoules used globally in 2016 alone [1]. The city of Calgary is known for its extreme weather conditions, thus making construction materials a crucial feature in houses. It contributes only a tiny fraction to the global carbon dioxide emissions, but to foster sustainable development of Canada, it is necessary to start at a community level.

Numerous countries have pledged to make reducing greenhouse gas emissions a priority by signing the Paris Agreement. Canada has signed the Paris Agreement and placed emphasis on promoting energy efficient products through numerous programs that can save homeowners up to $300 each year [2]. This study incorporates many energy efficiency products from these government approved programs to help decrease space heating costs.

The purpose of this study is to develop a lifecycle analysis for buildings that can be used to assess the total energy consumption and associated costs. It will allow building owners, commercial or residential, to make better decisions on how to modify their structures in term of energy efficiency. For the study, the scope is limited to specific houses. The research investigated the residential homes in the Calgary, Alberta region. The prices were based off local rates and were collected

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S. Walbridge et al. (eds.), *Proceedings of the Canadian Society of Civil Engineering Annual Conference 2021*, Lecture Notes in Civil Engineering 247,
https://doi.org/10.1007/978-981-19-0968-9_50

in August 2020. The temperature data used was from 2018 to 2020 from Environment and Climate Change Canada [3]. Data related to energy providers was collected from ENMAX [4]. Although the average size of a house in Canada is approximately 1900 square feet [5], a 2300-square-foot house in Airdrie, Alberta, was taken as representative residential home in Alberta to perform the case study. The representative residential home was chosen as it is the residence of the first author, therefore all home related details required were for the study were accessible. The presented work in this paper was developed from May to August 2020 where the first author was a research intern under the supervision of the second author.

The paper is divided into the following section. The methodology in form of a lifecycle analysis is presented in Sect. 2. A numerical example is provided in Sect. 3 to better illustrate the proposed approach. Section 4 contains the conclusions and recommendations for future work.

2 Methodology

The core of the proposed lifecycle approach is a thermodynamic analysis of the building of interest to assess the current and future heating requirements based on the temperature differential between inside and outside the building. The total energy consumption for heating of a building is determined based on the energy loss due to the temperature differential. Consider a homogeneous portion of the building envelope, the incremental energy loss during a short time interval $\Delta\tau$ is determined as follows:

$$E = UA\Delta T\Delta\tau \quad (1)$$

where E is the incremental energy loss of the considered element, U is the u-factor of the material, A is the area of the element, and ΔT is the temperature differential between inside and outside of the building. As the u-factor is material dependent, the energy loss is the sum over all n elements that belong to the building envelope:

$$E = \sum_{i=1}^{n} U_i A_i \Delta T \Delta\tau = \Delta T \Delta\tau \sum_{i=1}^{n} U_i A_i \quad (2)$$

In Eq. (2) it is assumed that the temperature difference between inside and outside the building is the same for all elements. The equation could be used to assess the total energy loss if the temperature difference ΔT would be time-invariant. Daily and sessional variations of the outside temperature must be considered. For example, Fig. 1 shows how the outside temperature fluctuates in a year, with summer months consisting of higher temperatures while winter has lower temperatures.

Figure 2 displays the hourly temperature change over 2 days, with cooler

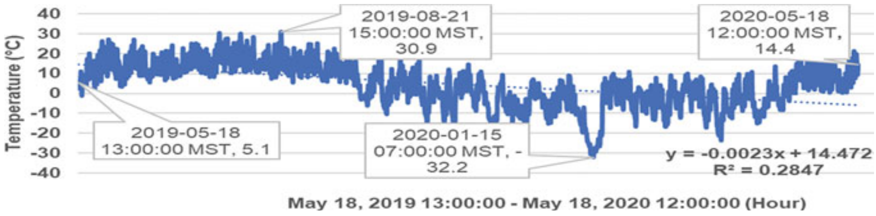

Fig. 1 Hourly outside temperature profile for the city of Calgary from May 18, 2019, 13:00:00 to May 18, 2020, 12:00:00

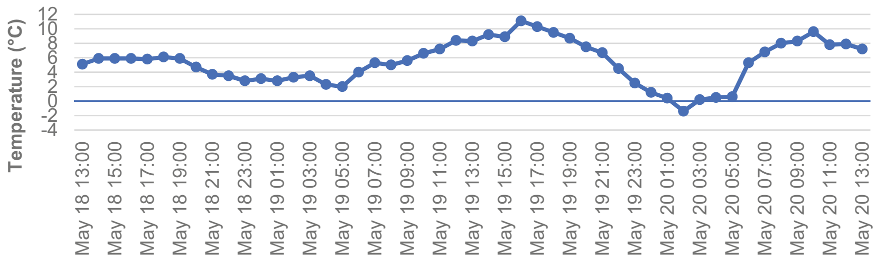

Fig. 2 Hourly outside temperature for the city of Calgary from May 18, 2019, 13:00 to May 20, 2019, 12:00

nights and warmer days, shown by the 12 °C gap between the highest and lowest temperatures.

To better account for the stochasticity of the sessional, sub-seasonal, and daily changes of the temperature difference ΔT, the thermodynamic analysis is discretized into hourly steps of $\Delta\tau = 1$ h. The total energy loss E_{tot} is then the sum of the incremental losses over the considered remaining lifetime of the building assuming the temperature differences ΔT_j are known:

$$E_{tot} = \Delta\tau \sum_{j}^{m} \Delta T_j \sum_{i=1}^{n} U_i A_i \tag{3}$$

Considering that air conditioning (if present) uses electricity and not natural gas, the only outside temperatures used for calculations were the ones that required the building to heat (below 20 °C):

$$If\ 20 - T_{outside} > 0, use\,in\,calculations\,as\,heating\,is\,required. \tag{4a}$$

$$If\ 20 - T_{outside} < 0, do\,not\,use\,in\,calculations\,as\,heating\,is\,not\,required. \tag{4b}$$

Based on Eq. (3), the total lifecycle costs c_E for heating can be determined. If the unit-energy costs c_0 would be time-invariant, the total costs c_E is simply $E_{tot}c_0$. However, as energy costs vary in time due to shorter term seasonal variations and long-term inflations, Eq. (3) is expanded to obtain the total costs for heating the building, which is equivalent to the total costs of the energy losses:

$$c_E = \Delta\tau \sum_{j}^{m} c_{0,j} \Delta T_j \sum_{i=1}^{n} U_i A_i \tag{5}$$

where $c_{0,j}$ is the cost per unit energy for time period j.

The total lifecycle costs c_{tot} must include any costs c_B incurred over the service life of the building that will be used to repair, replace, or upgrade on the building envelope. Any changes to the building envelope may affect the heating requirements. Hence, the sum of the heating costs c_E and the building improvement costs c_B needs to be considered:

$$c_{tot} = c_E + c_B \tag{6}$$

The objective is to minimize the total lifecycle costs of the building to achieve the most economical solution. This objective is a surrogate for the most sustainable design such as the case where the total energy consumption of the building due to construction, maintenance, and heating should be minimized in order to minimize green house gas emissions.

Equations (5) and (6) do not consider any energy losses due to small openings and cracks in the building envelope. Additionally, energy released in form of heat from electronic devices such as appliances, computers, lights are not taken into account. Solar heat is assumed to be negligible in this analysis. It is expected that the total energy consumption according to Eq. (3) will differ to the actual energy amount used for heating the building. To account for the factors that have not been considered in the analysis, a model correction factor will be introduced that is calibrated based on the actual amount of used energy. Details of the model calibration are provided in Sect. 3.

The overall methodology can be summarized in the following steps:

1. Retrieve u-factors of materials
2. Calculate the area each material encompasses on the building envelope
3. Evaluate differential temperature between inside and outside of the building over specified time period
4. Input energy costs for utility service provider
5. Perform lifecycle cost analysis.

The proposed lifecycle analysis in Eqs. (5) and (6) is implemented in a spreadsheet tool to have the ability of examining the cost benefit of upgrading one or more elements of the building envelope to achieve better insulation effects and reduce long-term energy costs.

3 Numerical Example

To illustrate the proposed lifecycle analysis in Sect. 2, a 2300-square foot detached house in Airdrie, Alberta, was analyzed. The building was constructed in July 2014, and a total lifetime of 50 years was assumed. It is a relatively new home at the early state of its lifecycle. Table 1 shows the areas and u-factors for all elements of the building envelope.

The areas of most elements were calculated from the existing drawing of the house that contains the dimensions of the house, while the rest of the areas were measured using a measuring tape. The u-factors in Eq. (5) and Table 1 are material specific. There are many different types of walls, roofs, windows, and doors and each of them can have different u-factors. The u-factors for some of the windows and doors were found by inputting the product code into the National Fenestration Rating Council (NFRC). The u-factor of walls and roofs was found by examining the u-factors appropriate for each of the zones in the Calgary region and selecting the best suited wall composition for the building being analyzed [7]. It is acknowledged that determining or finding u-factors may not be a trivial task.

It is assumed the inside temperature of the building remains constant at 20 °C. To predict future heating requirements for the building, it is necessary to have an

Table 1 Areas and u-factors for the elements of the building envelope

	A (ft^2)	*U* (BTU/ft^2 °F h)	*UA* (BTU/°F h)
Type of window			
Casement 635	46.79	0.4	18.71
Fixed 752	83.74	0.46	38.52
Horizontal slider 751	76.04	0.46	34.98
Single vertical hung 750	18.05	0.46	8.30
Fixed 637	59.46	0.45	26.76
Type of door			
Patio door	15.41	0.35	5.40
Front door	21.44	0.35	7.50
Sliding door	38.88	0.45	17.50
Garage door	22	0.16	35.20
Type of wall			
Normal	2922	0.057	145.83
Exposed basement	784	16.93	46.31
Type of roof			
Cathedral/Flat	297	0.035	10.42
Normal	979	0.017	16.60

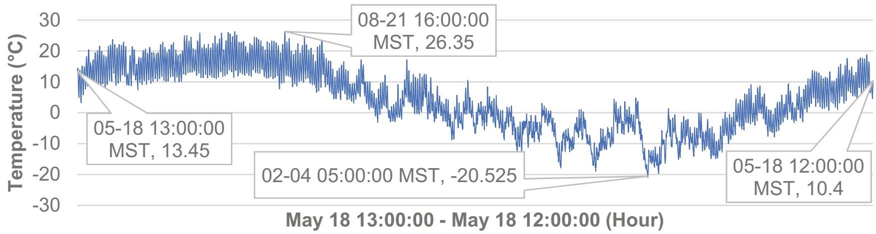

Fig. 3 Average outside temperature of 2016–2020 for the lifecycle analysis to forecast future heating requirements of the sample building

estimated outside temperature profile for the remaining lifetime of the building. As a first estimate, the average of four hourly temperature curves from 2016 to 2020 was used to obtain a somewhat "smoothened" outside temperature curve. Figure 3 shows the results of this analysis.

The temperature profile in Fig. 3 could be used without further modifications to predict the total heating energy and total lifecycle costs according to Eq. (6). However, since climate change occurs at 0.18 °C per decade [8], this effect was accommodated in the analysis by shifting the temperature curve in Fig. 3 upwards at rate of 0.018 °C/year. This linear increase of the outside temperature is a simple and effective way to incorporate the effect of climate change into the analysis where the required energy for heating the building will be slightly reduced by having more hours with a temperature above 20 °C. If more advanced and local results become available in future, the proposed lifecycle analysis can be easily adjusted to incorporate more accurate temperature predictions.

Determining the energy consumption according to Eq. (3) will inevitably result in a difference to the actual energy consumption. This effect occurs as models are developed based on simplifications and assumptions that leads to differences between models and reality. A multiplicative model error is introduced in (3) to improve the estimation of the energy consumption.

$$E_{tot} = \varepsilon \Delta \tau \sum_{j}^{m} \Delta T_j \sum_{i=1}^{n} U_i A_i \tag{7}$$

where ε is the model correction factor. It is estimated by comparing the energy usage from the energy bills (= actual energy consumption) with calculated values based on Eq. (3). Figures 4 and 5 blue represents the energy values calculated and orange represents the energy values from the energy bills.

As displayed by the two graphs above, the trend is quite consistent for the most part, indicating that the modeled values have a similar trend but is higher than the actual energy consumption. The fact that the actual and estimated energy consumptions are very similar is expected as the temperature differential ΔT is the primary factor for heating a building.

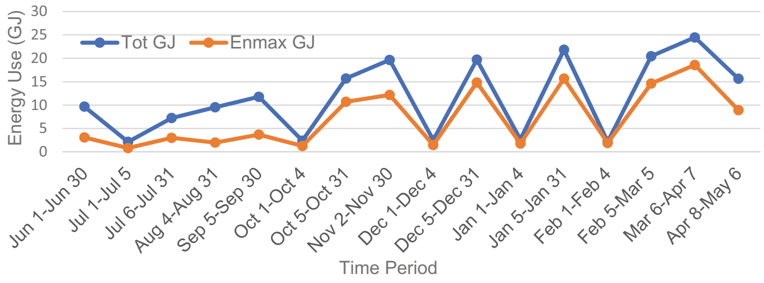

Fig. 4 Energy consumption comparison for the period from June 2019 to May 2020 without model error adjustment

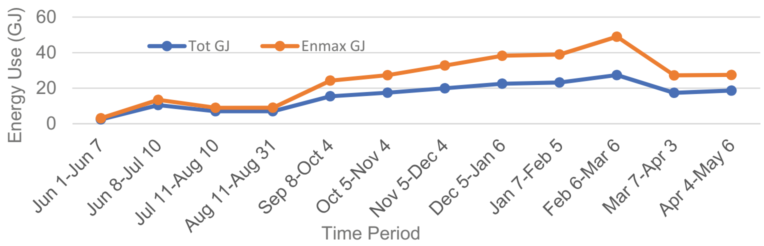

Fig. 5 Energy consumption comparison for the period from June 2018 to May 2019 without model error adjustment

To be able to make recommendations for improving the existing building envelope with an economical benefit, it is necessary to perform two analyses:

1. Estimate the lifecycle cost $c_{tot,0}$ based on the existing conditions of the building without introducing any alterations. This cost value represents a base value.
2. Estimate the lifecycle cost $c_{tot,mod}$ if one or more modifications are introduced in the building envelope that may lead to energy savings beyond the investment costs to obtain the modifications.

The objective is to find the modifications in the building envelope that will maximize the difference between the lifecycle costs from the two analyses:

$$\Delta c = c_{tot,0} - c_{tot,mod} \tag{8}$$

where $\Delta c > 0$ is the cost savings due to the proposed modification(s). If all possible alterations lead to a negative Δc, it means the existing building should not be modified or upgraded.

The costs of alternate building envelope elements that possess lower u-factors need to be found or determined. The lower the u-factor, the higher energy performance the material provides. Table 2 shows resources of high efficiency elements and the costs that were used in the analysis.

Table 2 Cost of new higher efficiency elements

Element	Cost ($)	Resource
Windows		
Casement	320	Home Depot [9]
Horizontal sliding	200	Home Depot [9]
Vertical hung	250	Home Depot [9]
Fixed	215	Home Depot [9]
Type of door		
Patio door	400	Home Depot [9]
Front door	190	Home Depot [9]
Sliding door	700	Home Depot [9]
Type of wall		
Stucco	7/square foot	Calgary Stucco [10]
Vinyl	5/square foot	Urban Siding [11]
Type of insulation		
Closed cell spray foam	4/square foot	Beyond Foam [12]

U-factors of the house were changed to its higher performing version, and after factoring the cost, the analysis was made based on that singular product change. This analysis allowed the effects of each sub-element change to be displayed visually on a graph, which made it easier to identify which house modification would decrease the energy levels and reduce costs the best.

As already mentioned, the entire analysis was implemented in a spreadsheet tool to allow home and building owners to perform their own analysis without the hassle of developing the numerical analysis. Figures 6, 7, 8 and 9 show a few screenshots of the developed tool.

The user has the option at the beginning of the analysis to select the preferred unit system and whether U or R values are in the analysis. R values are the inverse of u-factors.

The user is prompted with the questions in Fig. 7 to add in information regarding their home or building.

Default u-factors are provided in Table 3 if the user does not provide any values. For example, the u-factor of the garage door used is 0.16 (BTU/ft^2 °F h). The product of u-factor and area for the house was found to be 144.30 (BTU/°F h). These u-factors are taken from the Inspections Group, which comply with section 9.36 of the Alberta Building Code.

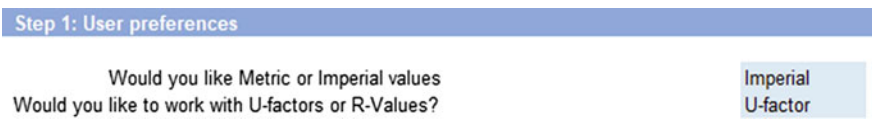

Fig. 6 User preferences

Step 2: House Specific User-Input

Fill out all known values, if unknown leave it blank

Walls

Do you have vinyl or stucco siding?	Vinyl

Area(ft2)	U factor (BTU/ ft2·°F·h)
500	0.1

Windows

Type of Window	Area(ft2)	U factor (BTU/ ft2·°F·h)
Fixed	10	0.5
Casement	12	
Vertical Hung	5	
Horizontal Sliding	10	

Outdoor doors

Type of Door	Area(ft2)	U factor (BTU/ ft2·°F·h
Front Door	25	
Patio Door	20	0.9
Glass Sliding Door	15	

Ceilings

Type of Ceiling	Area(ft2)	U factor (BTU/ ft2·°F·h)
Cathedral/Flat	200	
Normal	300	

Garage

Do you have a garage?	Yes
Is your garage attached to your house?	Yes
What is the area(ft2) of your garage?	200

Fig. 7 House specific user input

Step 3: Monthly Natural Gas

Are you on a fixed or floating payment plan?	Fixed			Please put a 0 if you are unsure of any values
What is your fixed payment rate/GJ?	4			
Do you know your monthly **payments** for natural gas?	Yes			
How many years of payment data are you able to provide?	☑ 2020	☑ 2019	☑ 2018	
Do you know your monthly **usage** for natural gas?	Yes			
How many years of usage data are you able to provide?	☑ 2020	☑ 2019	☑ 2018	

	2020				2019				2018		
	Start date(MM-DD)	End date(MM-DD)	Total PAYMENT($)		Start date(MM-DD)	Start date(MM-DD)	Total PAYMENT($)		Start date(MM-DD)	End date(MM-DD)	Total PAYMENT($)
1	01-01	01-31	90	1	01-01	01-31	100	1	01-01	01-31	90
2	02-01	02-29	90	2	02-01	02-29	90	2	02-01	02-29	90
3	03-01	03-31	90	3	03-01	03-31	90	3	03-01	03-31	90
4	04-01	04-30	90	4	04-01	04-30	90	4	04-01	04-30	90
5	05-01	05-31	90	5	05-01	05-31	90	5	05-01	05-31	90
6	06-01	06-30	90	6	06-01	06-30	90	6	06-01	06-30	90
7	07-01	07-31	90	7	07-01	07-31	90	7	07-01	07-31	90
8	08-01	08-31	90	8	08-01	08-31	53	8	08-01	08-31	90
9	09-01	09-30	90	9	09-01	09-30	90	9	09-01	09-30	90
10	10-01	10-31	90	10	10-01	10-31	90	10	10-01	10-31	90
11	11-01	11-30	90	11	11-01	11-30	90	11	11-01	11-30	90
12	12-01	12-31	90	12	12-01	12-31	90	12	12-01	12-31	90

	2020				2019				2018		
	Start date(MM-DD)	End date(MM-DD)	Total Usage(GJ)		Start date(MM-DD)	Start date(MM-DD)	Total Usage(GJ)		Start date(MM-DD)	End date(MM-DD)	Total Usage(GJ)
1	01-01	01-31	10	1	01-01	01-31	10	1	01-01	01-31	10
2	02-01	02-29	10	2	02-01	02-29	10	2	02-01	02-29	10
3	03-01	03-31	10	3	03-01	03-31	10	3	03-01	03-31	10
4	04-01	04-30	10	4	04-01	04-30	10	4	04-01	04-30	10
5	05-01	05-31	10	5	05-01	05-31	10	5	05-01	05-31	10
6	06-01	06-30	10	6	06-01	06-30	10	6	06-01	06-30	10
7	07-01	07-31	10	7	07-01	07-31	10	7	07-01	07-31	10
8	08-01	08-31	10	8	08-01	08-31	10	8	08-01	08-31	10
9	09-01	09-30	10	9	09-01	09-30	10	9	09-01	09-30	10
10	10-01	10-31	10	10	10-01	10-31	10	10	10-01	10-31	10
11	11-01	11-30	10	11	11-01	11-30	10	11	11-01	11-30	10
12	12-01	12-31	10	12	12-01	12-31	10	12	12-01	12-31	10

Fig. 8 Energy cost and usage input

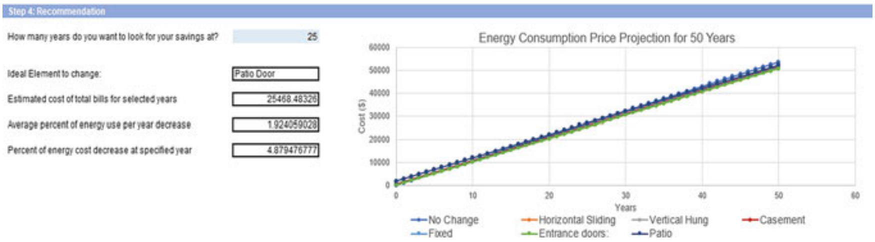

Fig. 9 User recommendation

Table 3 U-factors to replace blank user inputs

Sub-element	U-factors
Horizontal sliding window	0.46
Vertical hung window	0.46
Casement Window	0.40
Fixed window	0.45
Glass sliding door	0.45
Front door	0.35
Patio door	0.35
Cathedral/Flat roof	0.035
Normal roof	0.017

The energy usage was determined to be 47.36 GJ/year. The next step allows the user to input whether they have a fixed or floating payment for their energy bills, in Fig. 8, floating payment plan was chosen. which, in this sample picture the tool allows the input of a fixed payment rate/GJ. The user will then be asked if they have information on their payments and energy usage for each month. These values will be the preferred values in calculations.

The payment entries the payment/year was calculated to be an average of $1071.00/year. After applying the steps, the model error was determined to be 2.17. From calculations, it was evident that some of the elements did not significantly change energy or cost values, therefore, to provide a simpler user experience they were omitted in the final graphs. After subbing in modifications for the number of years that the user chose, Fig. 9 shows the recommendation that is presented to the user. The recommendation includes the element that will provide the best financial return over the elected years, the estimated sum of natural gas bills and the average cost and energy decrease per year.

4 Conclusion

In conclusion, the goal of creating a template that maximizes energy efficiency and money spent was successful. Our research suggests that for the sample house investing in quality patio doors would be the best course of action for the span of 25 years. On average the yearly energy usage decreased by 1.9% and the total energy cost decreased by 4.9% at the 25-year mark. It is important to note that ideally the user would input all the data relevant to their house, otherwise it may alter the results from the true values. Implementing these modifications are one step closer to reducing carbon emissions, and if implemented in a larger scale it will make a significant difference. This template has the potential to be altered for larger scale projects so that it is applicable to other cities and commercial buildings.

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Essential Elements and Best Practices for Teaching a Culminating Capstone Course Online in Construction Management Programs

H. Dang and W. Bender

1 Introduction

Capstone was in use as early as the late 1800s and became a common term in higher education in the mid-twentieth century. It referred to a culminating experience concluding an integrative and comprehensive experience in an educational program. Many Construction Management (CM) programs required a capstone course in the senior year of an undergraduate curriculum. The course often integrates and synthesizes knowledge gained from previous courses through a real-world project experience. This experience presents students with the ability to show fundamental knowledge and skills gained during their studies. As construction projects have become more complex, the capstone course has become more important to prepare students for professional careers and challenging projects.

Capstone courses in CM programs have various forms and configurations depending on program outcomes, accreditation requirements, and departmental and institutional resources. Figure 1 illustrates four forms and alternatives of CM capstone courses. The most common one is the projection option. Students are pursuing, competing, or managing construction projects. Often, the capstone courses use alternative project delivery methods and qualification-based selections. Students can prepare qualifications (e.g., description of past project experience, bonding capacity), estimates, schedules, site logistics, safety program and record, quality control, risk management, and subcontracts management. There are either a few major deliverables or many small assignments for students to complete a capstone project. When students are pursuing projects, they typically work on a Request for Qualification

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S. Walbridge et al. (eds.), *Proceedings of the Canadian Society of Civil Engineering Annual Conference 2021*, Lecture Notes in Civil Engineering 247,
https://doi.org/10.1007/978-981-19-0968-9_51

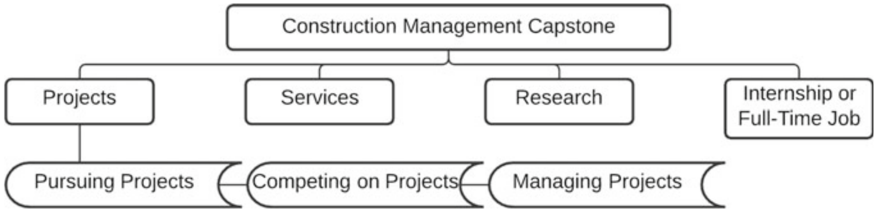

Fig. 1 Various forms and alternatives of construction management capstone courses

(RFQ) and a Request for Proposal (RFP) along with their design, estimate, schedule, and others. When students are managing projects, they often focus on estimates, schedules, site logistics, safety, cost controls, submittals, and financial performances. Some capstone courses use regional or national student competition projects such as Associated Schools of Construction (ASC), Mechanical Contractors Association of America (MCAA), American Society of Civil Engineers (ASCE), or National Association of Home Builders (NAHB) student competitions.

Some capstone courses offer an option to provide services to local communities (e.g., Habitat for Humanity). Service projects are extremely valuable to local communities and have a direct impact on different organizations. Therefore, some researchers have investigated service-learning for a culminating capstone experience.

In exceptional cases, a capstone course can be an undergraduate research project under the approval of a faculty advisor. Research projects offer students an excellent opportunity to work with a faculty advisor on frontier topics in the construction industry. For example, many research projects involve data collection from general contractors or investigating organizational issues or technology applications.

Internships or full-time job experiences sometimes are used as an alternative to capstone courses. However, this option is uncommon and likely to be eliminated. It is worth pointing out that some construction management programs may mandate a certain number of internships for graduation requirements. They are unlikely to use internships to replace capstone courses due to a lack of control and assessment.

The knowledge gap of this research is to investigate essential elements and best practices to teach the CM capstone course online. In the past, construction management capstone courses were often taught in-person in a face-to-face environment despite various forms and alternatives, simulating real-world projects and experiences. However, most courses changed to online instruction because of an outbreak and ongoing surges of a pandemic. As a result, online CM capstone courses faced many challenges for real-world project-based learning. To investigate essential elements and best practices to teach the course online, the authors select instructors who have at least taught capstone online one time to collect qualitative data. We aim to explore the following two research questions in a time-sensitive environment.

1. What are the essential elements for teaching construction management capstone courses online?

2. What are the best practices for teaching construction management capstone courses online?

2 Literature Review

The authors collected literature from three organizations: the American Society of Civil Engineers, the American Society of Engineering Education, and the Associated Schools of Construction. The authors initially collected more than 100 articles, subsequently selected about 30 papers, and ultimately identified less than ten articles closely related to construction management capstone courses.

2.1 Capstone Course

Capstones offer a culminating experience and prepare students for professional careers in the construction industry. Traditional courses and pedagogies focus on specific knowledge content, while capstones require critical-thinking and problem-solving based on a real-world project. Many researchers have revealed a significant variation of capstone course delivery, including but are not limited to course duration, project scope, project source, project selection, faculty involvement, industry participation, team assignments, a mixture of specialties or disciplines, number of participants, and evaluation processes [1]. Luo and Hyatt [2] summarized several key elements, including extended time frames, interdisciplinary or multidisciplinary teams, service-based or real-world projects, open-ended problems, professional issues, technology tools, faculty and industry mentorship, and job-ready skill performance [2, 3].

Narrowly focusing on construction management programs, the authors synthesized capstone projects in three categories below.

- Qualification-Based Selection Projects
  - Request for Qualification (RFQ)
  - Request for Proposal (RFP)
  - Early estimate and schedule and sometimes detailed estimate and schedule
  - Building Information Modeling
  - Emphasize on oral presentations
- Competition Projects
  - Specific problem or project
  - Subcontract preparation
  - Detailed estimate and schedule
  - Site logistics
  - Safety

  - Construction management approaches
  - Risk management
- Construction Projects
  - Site logistics
  - Cost control
  - Financial performance.

2.2 Online Teaching

Online teaching became a mandated requirement of higher education in March 2020 because of the coronavirus disease 2019 (COVID-19) pandemic. The COVID-19 pandemic forced universities to shift from in-person to online teaching. The courses that were traditionally taught in-person had many difficulties in the shift and required more preparation time for the online course delivery.

The mandated online teaching changed pedagogies and environments for teaching and learning. Some teaching practices suddenly became difficult or impossible to perform. These included but were not limited to building rapport with students, hosting office hours, humanizing online courses, using a whiteboard for notes and demonstrations, and maintaining social presences. Some others were carried over to online teaching but delivered differently. These were Universal Design for Learning and diverse and inclusive teaching. Some main characteristics of online learning are 1) blended instructions using reading materials, recorded videos, and live meetings; 2) intensive uses of technologies for engagement and empowerment; 3) a balance of course flexibility and student's motivation; 4) a shift towards self-regulated learning.

3 Research Design

The authors used a qualitative approach to investigate the essential elements and best practices for teaching CM capstone courses online. First, the authors discussed their teaching background and positionalities in the research design. Second, the authors analyzed capstone course syllabi and identified top-ranked student learning outcomes by frequency. Third, the authors conducted seven semi-structured interviews with capstone course instructors. Figure 2 illustrates the workflow of research data collection. The authors sent a one-minute survey to the Associated Schools of construction and Construction Research Congress communities to recruit participants. The survey collected if they were willing to participate in a semi-structured interview and their contact information. The survey had 21 responses. Of which, 16 completed the survey. The authors contacted nine and conducted seven semi-structured interviews.

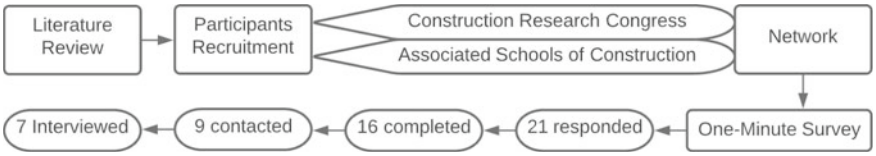

Fig. 2 Research data collection workflow

3.1 Background and Positionalities

The authors have extensive teaching experience in construction management capstone courses. Author A taught capstone five years in a construction engineering and management program and two years in a construction management program. The former was a concurrent simulation of a real-world design-build project with a mix of students from civil engineering and construction engineering and management. The course was offered in both Fall and Spring semesters (i.e., 16 weeks per semester) to a range of 75–150 students. Students typically worked in a team of eight. Each student was specialized in one role or discipline. These roles included but were not limited to architects, structural engineers, geotechnical engineers, civil and site engineers, transportation engineers, hydrology and environmental engineers, mechanical engineers, electrical engineers, estimators, schedulers, construction managers, and Leadership in Energy and Environmental Design (LEED) specialist. There were four major deliverables, including a request for qualification (RFQ), preliminary design notebook, request for proposal (RFP), and oral presentation. About two instructors and one or two teaching assistants delivered the course working with assistance from one faculty advisor for each role or discipline. The latter was an immersive real-world construction project for construction management students. The course spanned in Winter and Spring quarters (i.e., 10 or 11 weeks each quarter) and had a range of 12–31 students. Students worked either individually or in a team of four or fewer members. There were seven deliverables, including project selection and approval, introduction, estimates and schedule, planning and site logistics, construction management, project report, and oral presentation. Both capstone courses had two one-hour lectures and one two-hour lab for each section.

Author B has taught capstone at three universities, a civil engineering design-based capstone, and a project-based capstone for construction management students. The most recently taught capstone courses were individually, and for one year, students had an option of two-person team-based projects. Projects were based on real projects that had not been constructed yet. Students were required to find the projects from the local industry, and thus each project was unique. Deliverables included estimates, schedules, written proposals, safety plans, risk analysis, logistic plans, and oral presentations to an industry panel. All courses were face to face except for online courses in the spring and summer of 2020.

3.2 Content Analysis of Course Syllabi

The authors collected five syllabi from seven research participants in American Council for Construction Education (ACCE) accredited programs. The two unavailable course syllabi were Accreditation Board for Engineering and Technology (ABET) accredited programs. Thus, they were not included in the analysis of ACCE student learning outcomes. To optimize results, the authors included two syllabi, one from each author, in the analysis. The authors counted the student learning outcomes in the collected syllabi. These student learning outcomes were then ranked from the most to least frequent.

3.3 Semi-structure Interviews with Course Instructors

The authors conducted seven semi-structured interviews with nine contacted participants. Of these nine participants, one withdrew at the beginning of the interview, and one did not confirm a scheduled time or respond to further email communication. Each semi-structured interview lasted about 25 min, with five main questions below guiding the conversation.

1. What are the general information and requirements of the capstone course in your program?
2. Do you assess any student learning outcomes (SLOs) in the ACCE for your capstone course? If so, what are these SLOs?
3. What are the essential elements for teaching construction management capstone courses online?
4. What are the best practices for teaching construction management capstone courses online?
5. How do you ensure a culminating experience in capstone?

4 Results and Discussions

Research participants have a minimum of one year of online teaching experience for construction management capstone courses. Figure 3 shows the years of teaching, teaching capstone, and teaching capstone online for sixteen survey respondents. Of which, seven participated in semi-structured interviews, including participants A, B, C, D, F, M, and N.

Most participants taught a required, one-semester construction management capstone course in the senior year of a four-year program. The course had a range of 10–45 students. One participant stated that a capstone course had a maximum of 25 students in enrollment because of intensive work from the course instructor. The course might enroll up to 35 students with a teaching assistant for the course

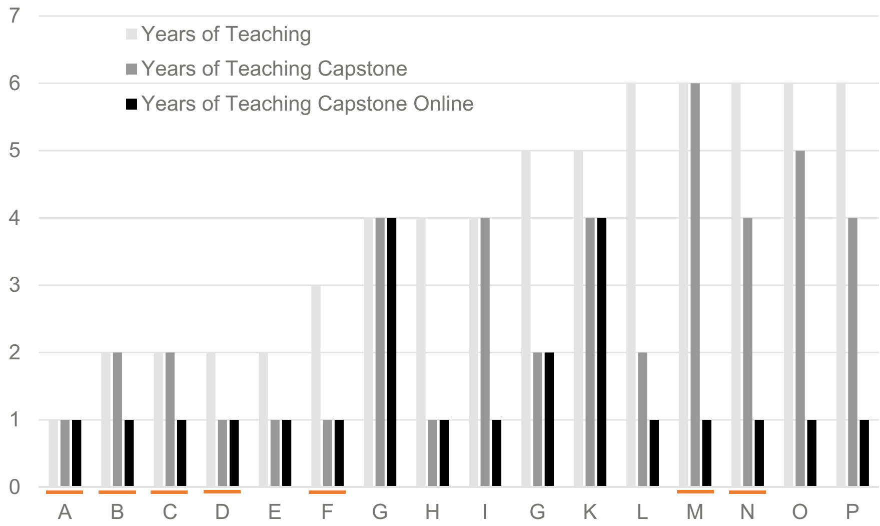

Fig. 3 Teaching experiences of survey respondents and interview participants

instructor. Among seven participants, five had students who worked in teams, one had a mix of team and individual work, and one had individual work only. We found that five capstone courses had construction management students only in ACCE accredited programs. Two capstone courses had students in multidisciplinary teams. These two courses were in ABET-accredited programs.

While all CM capstone courses focused on reading plans and specifications, estimate, schedule, site logistics, safety, risk management, each course had unique content meeting requirements from the industry advisory council or geared towards specific program outcomes. Most capstone courses typically span for one semester or two quarters. However, some construction programs offer one capstone course for multiple semesters or quarters to enhance comprehensive preconstruction and construction management practices. In addition, other construction programs provide a unique capstone course for each specialization or discipline.

4.1 Student Learning Outcomes

Capstone courses in ACCE accredited programs meet one or more of the 20 required Student Learning Outcomes (SLOs) for bachelor's degree programs in construction. Although the course may include other SLOs at the course, program, general educational, institutional, or university levels, ACCE SLOs are universal metrics for evaluation and comparison.

Students who graduated from these ACCE accredited programs shall be able to:

1. Analyze construction documents for planning and management of construction processes.
2. Create written communications appropriate to the construction discipline.
3. Create a construction project safety plan.
4. Create construction project cost estimates.
5. Create construction project schedules.
6. Understand the role of the construction manager as a member of different multidisciplinary project teams.
7. Apply electronic-based technology to manage the construction process.
8. Create oral presentations appropriate to the construction discipline.
9. Analyze professional decisions based on ethical principles.
10. Analyze methods, materials, and equipment used to construct projects.
11. Understand different methods of project delivery and the roles and responsibilities of all constituencies involved in the design and construction process.
12. Understand construction risk management.
13. Understand construction project control processes.
14. Understand the basic principles of sustainable construction.
15. Apply basic surveying techniques for construction layout and control.
16. Understand construction accounting and cost control.
17. Understand the legal implications of contract, common, and regulatory law to manage a construction project.
18. Understand the basic principles of structural behavior.
19. Understand construction quality assurance and control.
20. Understand the basic principles of mechanical, electrical, and piping systems.

Based on five syllabi from participants and two syllabi from the authors, top-ranked SLOs are shown in Table 1. It appeared all syllabi focused on SLO#7 apply electronic-based technology to manage the construction process for online capstone courses. The following four equally ranked SLOs were related to analyzing construction documents, methods, materials, and equipment and creating cost estimates and schedules to manage the construction process and construct the construction project.

4.2 Course Models and Examples

Research participants generally taught capstone courses in two models: A and B. In Modal A, a course instructor works with industry mentors or faculty advisors to deliver one or more projects in a capstone course. Often, students work in teams, especially when using industry mentors. Sometimes, students work individually or perform a mix of individual and team assignments. Model B requires multiple capstone courses, breaking down into residential, commercial, heavy civil, or mechanical. Both models can have an engineering design component in capstone

Table 1 Student learning outcomes of construction management capstone courses

SLO#	I	II	III	IV	V	VI	VII	Total
7	1	1	1	1	1	1	1	7
1		*1*	*1*	*1*	*1*	*1*		*6*
4	*1*		*1*	*1*	*1*	*1*		*6*
5	*1*		*1*	*1*	*1*	*1*	*1*	*6*
10	*1*	*1*	*1*		*1*	*1*	*1*	*6*
3	1	1	1	1		1		5
8	1		1		1	1	1	5
9		1	1	1	1	1	1	5
2		*1*	*1*	*1*		*1*		*4*
6		*1*	*1*		*1*	*1*	*1*	*4*
12			1	1				3
13		1	1				1	3
16	1	1					1	3
14	*1*						*1*	*2*
18		*1*	*1*				*1*	*2*
11			1				1	1
15								1
17		1						1
19	1							1
20								*0*

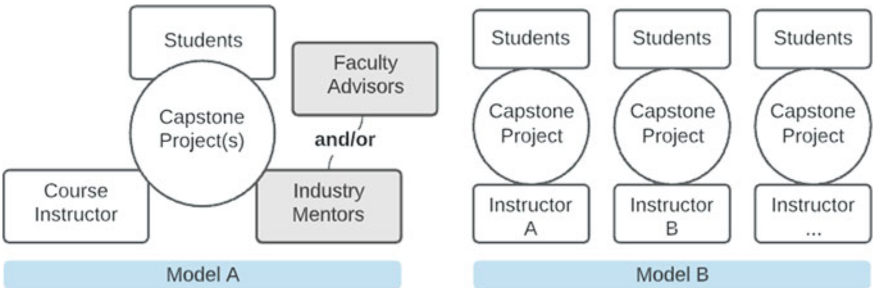

Fig. 4 Models for construction management capstone courses

projects, especially when the course has multidiscipline such as civil engineering, architectural engineering, and construction management (Fig. 4).

4.3 Essential Elements and Best Practices

Based on semi-structured interviews, participants revealed multiple essential elements and best practices in three categories: (1) course content, (2) student work, and (3) assessment and feedback. Course content consisted of the design, development, and delivery of a capstone course. Course instructors typically selected real-world projects based on project descriptions shared by industry sponsors. Sometimes, instructors allowed students to choose a project of their interest under certain criteria. The instructors needed to review and approve a student's project before it could be used for the capstone course. The project included construction documents such as plans and specifications. Students would analyze these documents and prepare their estimates, schedules, site logistics, and other required tasks. Projects further progressed in construction required safety programs, quality control, risk management, and financial performances. It was also essential to include interactions with industry mentors or faculty advisors. Some courses had specific instructions for mentor meetings. Others used industry mentors as guest speakers or judges.

Student work should be self-driven and proactive in either major team deliverables or small individual assignments in the capstone course. Often students who were not self-driven or proactive would procrastinate or seek answers at the last minute. Unfortunately, these students needed to understand the expectations at the beginning of the capstone course. Students who were self-driven and proactive would ask questions, use resources, and engage in continuous learning activities. These students performed well and often pleasantly surprised others because of their excellent work and deliverables. Students should plan time to work on the capstone project every day. Taking the work seriously and treating it as a real job was critical to students' learning and performing tasks successfully.

Research participants emphasized assessment on both technical and professional skills as previous courses only focused on technical content. If students were working in teams, two peer evaluations should be conducted at the middle and end of the course. The middle evaluation should be openly shared within each team for constructive feedback. The end evaluation should be confidential to the instructor. The authors recommended the standard category method for the middle evaluation and Michaelson Method for the end evaluation. Assessment should be consistent with timely feedback. Each assignment or deliverable should have a grading rubric that clearly explains expectations. When it is challenging to maintain consistent grading for different projects, instructors should use the best professional judgment or consult with industry mentors for assessment and feedback. Timely feedback enabled students to learn from their past performance (Fig. 5).

Since capstone courses are often real-world projects, it is important that students analyze and respond to professional issues or unforeseen incidents. For example, one participant described a four-week exercise for an unforeseen incident on a capstone project. Industry partners developed these unforeseen incidents to capture real-world problems and risks in construction projects.

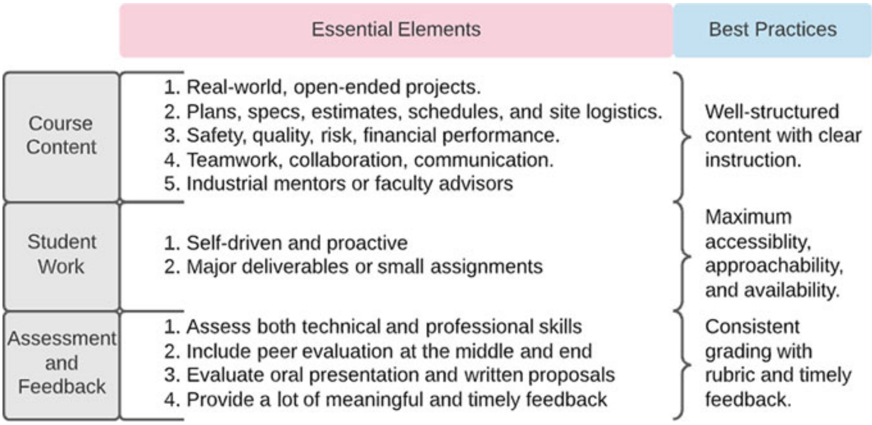

Fig. 5 Essential elements and best practices for teaching CM capstone course online

4.4 Online Teaching for a Culminating Experience

Most participants shared that resources should be abundantly available, and students should have access to software and technology support. The use of Google Drive, CATME, or Basecamp for sharing documents would help teamwork and collaboration. Students also need remote access to technology such as scheduling, estimating, and other software. The instructor should record each meeting so that students could watch later if they missed a meeting.

Although multiple disciplines were observed in civil engineering and architectural engineering programs, construction management programs remained exclusively for construction students, with different students taking on different roles. Integrating architects and engineers would be useful for alternative project delivery methods such as design-build and integrated project delivery. A traditional construction project might not require multidisciplinary teamwork for culminating experience. When possible, it was recommended to incorporate sustainability, Building Information Modeling (BIM), and preconstruction activities in a construction management capstone project.

During COVID-19 restrictions Zoom or MS Teams was used for class, mentor sessions, and presentations. The use of a virtual platform enabled class meetings, presentations, and mentor sessions to continue. Some form of a Learning Management System (LMS) (i.e., Canvas or Blackboard) was used to communicate, manage, grade, and update the online course.

5 Conclusions and Recommendations

The authors described the most important student learning results, two capstone course templates, and several essential elements and best practices. These essential elements for course content are (1) Utilizing real-world, open-ended tasks, (2) providing proposals, requirements, forecasts, schedules, and site logistics, (3) integrating ethical issues and financial analysis, (4) conducting collective collaboration, and (5) engaging with industrial mentors or faculty advisors were the essential elements for course material. Students needed to be self-motivated and constructive with their deliverables. The essential elements for appraisal and reviews were (1) testing both technical and professional expertise, (2) providing peer review at the middle and end of the course, (3) reviewing oral presentations and written submissions, and (4) providing students with a large amount of constructive and timely feedback. Some of the best practices included but were not limited to (1) well-structured material with straightforward guidance, (2) optimal usability, approachability, and affordability, and (3) accurate grading with rubrics and timely reviews. In addition, the reviewer summarized novel methods for online schooling.

The authors made the following recommendations for teaching CM capstone course online.

1. Incorporate small projects or examples in previous courses so that students are familiar with the process.
2. Assess each SLO directly or indirectly in previous courses at least once before assessing the SLO in the capstone course. Several SLOs that require the student to "create" are and should continue to be directly assessed in the capstone.
3. Resources need to be abundantly available, and technologies need to be remotely accessible to students.

Acknowledgements The authors thank the ASC network and CRC community for research participant recruitment. We appreciate the seven participants taking the time to share their experiences with us.

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